In presenting the dissertation as a partial fulfillment of the requirements for an advanced degree from the Georgia Institute of Technology, I agree that the Library of the Institute shall make it available for inspection and circulation in accordance with its regulations governing materials of this type. I agree that permission to copy from, or to publish from, this dissertation may be granted by the professor under whose direction it was written, or, in his absence, by the Dean of the Graduate Division when such copying or publication is solely for scholarly purposes and does not involve potential financial gain. It is understood that any copying from, or publication of, this dissertation which involves potential financial gain will not be allowed without written permission.

7/25/68

A STUDY OF SOME PARAMETERS AFFECTING

THE SHARPNESS RETENTION OF CUTLERY

Approved:

Chairman

Date approved by Chairman

A STUDY OF SOME PARAMETERS AFFECTING

THE SHARPNESS RETENTION OF CUTLERY

A THESIS

Presented to

The Faculty of the Graduate Division

by

Robert Norton Lukat

In Partial Fulfillment

of the Requirements for the Degree

Master of Science in Metallurgy

Georgia Institute of Technology

December, 1971

ACKNOWLEDGEMENTS

The author wishes to express his sincere thanks to Dr. N. N. Engel for his invaluable guidance and boundless patience during the progress of this study. Without his timely guidance and acute insight, this study would not have reached its present state of development. To Dr. Engel, the author owes a lifetime of indebtedness for the guidance he rendered in the development of the author's technical and engineering competence.

To Mr. E. A. Anderson of Southern Saw Service, Inc., the author owes a special note of thanks for his continual encouragement and experienced insight into the problems encountered during the progress of this work. The author wishes to thank Mr. W. C. Pattillo and Mr. Albert Maxwell, also of Southern Saw, for their cooperation and aid in the preparation of the knife specimens and the imaginative construction of the knife testing apparatus.

Mr. Charles R. Blackwood of Georgia Tech helped the author numerous times, in bringing his ideas for devices and equipment into practical fruition, the author wishes to recognize this valuable aid.
Dr. Helen E. Grenga and Dr. Stephen S. Spooner deserve a great deal of thanks for reviewing this work, especially in view of the highly practical subject matter involved.

The author would also like to thank Mr. T. H. B. Sanders, Jr., a fellow graduate student, for his aid in a computer program that greatly speeded evaluation of much of the data. Drs. Miroslav Marek and

E. A. Starke, Jr. offered the author a great deal of encouragement during his tenure at Georgia Tech, their support is genuinely appreciated.

The author must especially thank his devoted wife, Suzanne, for her unfailing love and encouragement during the preparation of this thesis. The author is very grateful to his parents for their many years of sacrifice, love, and understanding, sufficient thanks for what they have done for the author could never be adequately expressed. Special thanks are also due the author's parents-in-law for their interest and encouragement during the course of this work.

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

LIST OF TABLES

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (Continued)

LIST OF ILLUSTRATIONS (Continued)

SUMMARY

A study of some of the parameters affecting the sharpness retention of cutlery was made. The optimum edge configuration for a knife blade made of 440C stainless steel was determined.

It was found that the cutting edge angle, the blade thickness at the cutting edge, the material's hardness, and the surface finish of the cutting edge were most influential in determining the sharpness retention and cutting ability of the knife. The investigation revealed that the cutting edge angle and the thickness of the blade at the cutting edge were essentially independent and, therefore, could be separately optimized.

The cutting edge angle was optimized by constructing dulling curves, plots of sharpness versus number of dulling strokes, for knives of cutting edge angles varying from 11.5 degrees to 84 degrees. Analysis of these curves showed the best cutting edge angle to be between 44 and 48 degrees.

The best blade thickness at the edge was obtained by optimizing the ability of the edge to penetrate a paraffin block in conjunction with the stress-strain characteristics (toughness) of 440C stainless steel of varying hardness and thickness. For 440C stainless steel of Rockwell "C" 54 the thickness ranged from .015 inch for low load levels to .0225 inch for high load levels. For 440C stainless steel of Rockwell "C" 60 the thickness ranged from .008 inch for load load levels to .019 inch for high load levels.

The influence of the blade hardness on the sharpness longevity was studied by preparing dulling curves for knives ground to the optimum configuration as determined by the previous experiments. It was found that a marked increase in the sharpness retention could be obtained without loss in the other favorable characteristics of the blade material.

Extensive optical observation of the cutting edge during the progress of the experiments established the need for a smooth, uniform surface finish in the cutting edge. It was found that the edge should be finished on a fairly fine grit (about 600 grit), but that a polished surface was neither necessary nor desirable.

CHAPTER I

INTRODUCTION

Throughout history man has been concerned with the task of making tools, especially tools with sharp edges for cutting and piercing.

The problem of producing a good, sharp edge plagues man even today, especially with the product-oriented society of today.

As with all sciences or incipient technology, the first steps taken are by trial and error. From this experience, certain individuals develop a marked skill in the technique and then, to protect themselves from competition, guard their techniques in secrecy. This has been especially true in the production of knives and sharp edges.

In the case of the sharp edges for chip forming type tools, i.e., metal working tools, the shroud has been removed and in its place accurate information on tool shape, material, and hardness is available. Professional cutlery, for meat cutting, has not yet reached this stage of development. The ability to produce a good, sharp, long lasting edge is still an art known to only a few individuals, most of whom belong to families that have handed the art down from father to son for generations.

Previous work in this area, if any exists, is unpublished. This state of affairs is to be expected in view of the competitiveness of the cutlery industry. A second hindrance has been the lack of a technical background in the cutlery industry. Recently, new alloys for cutlery have been tried and their introduction is beginning to stimulate further investigation. Even so, there is still a reluctance to change. The methods an apprentice spent many years learning from the master are not easily laid aside or even modified. This situation is dramatically illustrated by the fact that few men, who have spent their lifetime making and sharpening cutlery, have ever observed a knife edge under a macroscope.

It is the purpose of this work to try to develop a systematic approach to the problem of obtaining a sharp edge, and, thereby, produce a technique whereby quality cutlery may be easily obtained. The first problem was that of identifying the characteristics of the knife which affect sharpness and the length of time the knife could remain sharp. After these characteristics or parameters were isolated, the influence of each parameter on sharpness and sharpness longevity was investigated. Finally, from these results the various parameters were concurrently analyzed to obtain the optimum configuration for the longest lasting sharp edge.

The initial background for this study was based on sharpness testing techniques used in the razor blade industry.[4] The sharpness test used was a measure of the energy absorbed in cutting, as well as the smoothness and completeness of the cut. The test was carried out as follows:

1. A thin fiber (about the thickness of a hair or whisker) of a polymer was mounted vertically, rigid at the lower end, free at the upper end.

2. A razor blade to be tested was mounted on a pendulum suspension so that it could cut the fiber without interference from the mounts.

3. The blade was raised to an appropriate height and allowed to swing against the fiber.

Depending on the sharpness of the razor blade, the fiber would be cut cleanly, partially cut and then torn, or not cut at all. The energy absorbed in cutting was measured by observing the difference in the height of the pendulum after the cut and the height of the pendulum swing without a fiber in place. Repetition of this test fairly accurately reproduced the dulling encountered by a razor blade during normal usage. Thus, it was possible to control the complex variables encountered in the cutting of a razor blade and better evaluate the importance of each factor. This standard was soon replaced by an optical evaluation that was very much faster and could be used as a quality control check.

The previous test of cutting ability revealed some important facts about cutting in general. It was found that lubrication of the cutting edge during cutting was just as important as the condition of the edge. Reducing the friction between the edge and the material being cut lengthened the life of the edge and insured a smoother cut. A second factor that revealed itself during these studies was the role of corrosion of the edge. The deterioration of the edge of the blade due to corrosion from the environment, including oils and acids found on the face as well as the water, severely limited the useful lifetime of the blade.

This background provided the starting point for the cutlery study. Several experiments proved that the "pendulum cutting" test would not be applicable to cutlery because 1) cutting meat is a rather gross event (in size) compared with cutting fibers, and 2) the cutlery edge was not dulled by the test, at a realistic rate.

The dulling effect of several types of cutting board materials on cutlery was studied by Mr. N. A. Milone at the University of Michigan, Department of Environmental Health, School of Public Health[1,2]. The emphasis of the work was on providing a cutting board that was sanitary and had a minimal dulling effect on the knife. The work done by Milone provided a sensible means of testing sharpness and of dulling the edge in a controlled manner.

After several modifications to Milone's design, the machine was able to meet the requirements of this study. After several refinements, the machine was able to provide a means of 1) giving an accurately controlled dulling rate, 2) measuring the sharpness of the edge without influence from the frictional forces of cutting, and 3) providing a controlled stroke length and pressure for measuring ease of penetration of the blade into a material.

Several characteristics were isolated that proved to affect the cutlery quality. They are 1) the angle at which the cutting edge is ground, 2) the thickness of the blade at the cutting edge, 3) the quality of the finish of the cutting edge, 4) the hardness and toughness of the blade material, and 5) the material being cut. The concurrent optimization of these factors is the ultimate goal of the following pages.

CHAPTER II

EQUIPMENT

Knife Grinding Machines

The knife edge preparation was done on a set of machines produced by the Nicholas Equipment Company of Sandusky, Ohio. Nicholas' machines are well known in the cutlery and sharpening industry. Machine preparation of the knives was chosen for several reasons. First, hand grinding of knife edges, at best, is rather random. Although, proficiency could be achieved for grinding one angle, the need for a variety of angles would have made hand grinding of all the knife specimens an excessively time-consuming task. Second, the machine preparation allowed exact replication of a given angle at any desired time. And third, the quality of the edge finish could be controlled and consistently reproduced.

All the knife specimens used in this study were hollow ground as the first step in their preparation. After the hollow grind, the edge angle was ground. Both steps were done on machines so that the results could be duplicated if more specimens were needed at a later date.

Hollow Grinding Machine

Hollow grinding has become a popular treatment for knife edges because of the increase in cutting efficiency obtained by adding this concave bevel to the leading edge of the knife (see Appendix for further discussion).

The hollow grinding machine consists of two cylindrical disc grinding wheels (1) (numbers in this section refer to Figure 1), electric drive motor, V-belt drive system, integral wheel dressing (2), and a cooling system (3) (4). The abrasive wheels (1) are each one and one quarter inches thick and from eight to twelve inches in diameter. The wheels are driven on a V-belt system by a single electric motor. Because of the drive mode, the wheels turn in the same direction. The machine design is such that the abrasive wheels may be moved along their centerline, thereby making the gap between the wheels variable from tangency to several inches separation. The gap is adjusted by a screw on the side of the machine (5). This adjustment controls the amount of hollow grind given a knife as well as correction for wheel wear.

The cooling system provides coolant flow into the grinding area in order to keep the knife edge cool and to flush the grinding products from the machine. A standard impeller pump (6) and settling tank (7) are employed externally to circulate and cleanse the coolant. The flow rate of the coolant is controlled by a valve on the front of the machine (8).

Edge Thickness Tester

The thickness at the edge is controlled by the hollow grinding given the knife. The hollow grinding wheels were set at tangency so that any thickness could be produced. In order to determine the thickness of the knife edge a gauge was deviced to measure the thickness of the edge .030 inch from the edge. Measuring .030 inch from the edge allows for metal removed during the edging process that follows the hollow grinding.

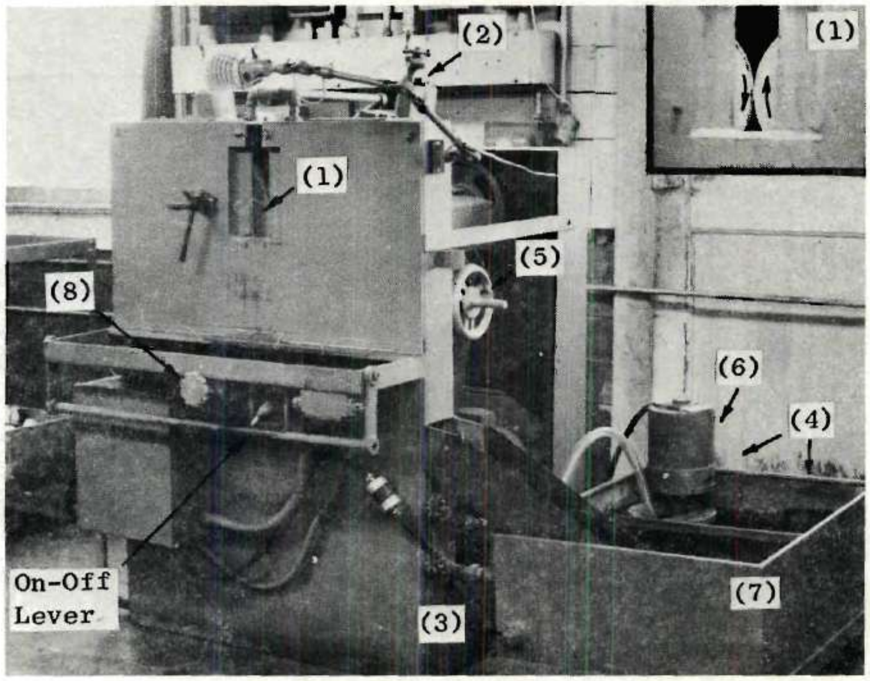


Figure 1. Nicholas Hollow Grinding Machine. Insert is Detail View of Abrasive Wheel Configuration, Arrows Indicate Wheel Rotation. Numbers Refer to Discussion in Text.

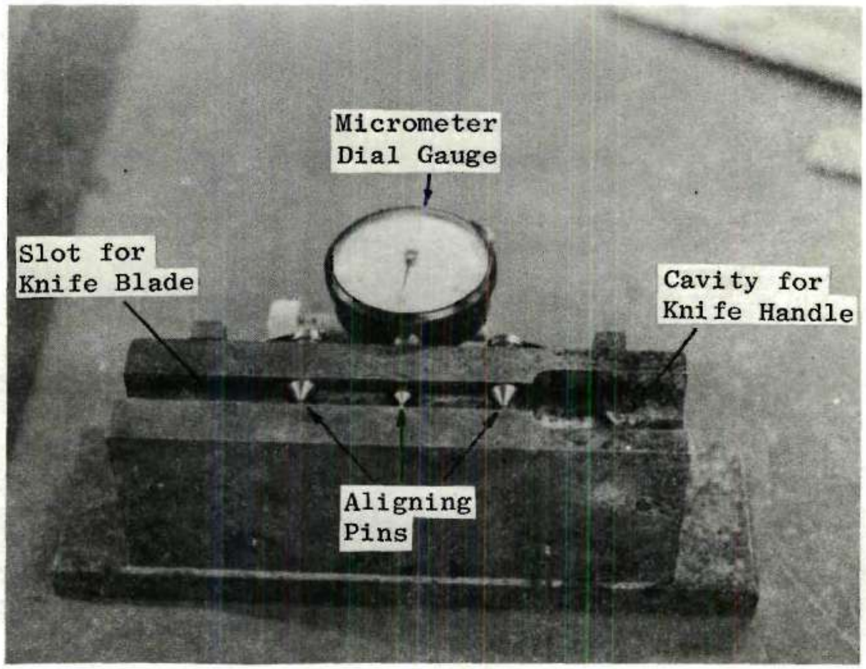


Figure 2. Edge Thickness Indicator.

This device, shown in Figure 2, was designed and constructed by Mr. Albert Maxwell of Southern Saw Service, Inc. for measuring the thickness of the knife at a set distance from the edge of the knife. The tester consists of a slot in a block of steel into which the knife is inserted, three spring loaded conical points for aligning the blade, and a micrometer dial gauge. The middle pin is coupled to the gauge such that it reads the gap thickness, and therefore the knife thickness, in thousandths of an inch. The tester allows the hollow grinding machine operator to follow the progress of the hollow grinding operation.

Edge Grinding Machine

Producing the cutting angle on the edge of the knife is a two-step process. The edge is shaped on the first edging machine with a set of coarse grit wheels. The second step uses a similar machine with a set of finer grit wheels. These wheels "finish" the edge by producing a smoother, flaw free edge.

The two abrasive wheels in this machine are cylindrical, about seven inches in diameter and roughly six inches thick. Each wheel has a spiral groove approximately one and one half inches deep cut into the surface. The wheels rotate counter directionally to each other. A crank (1) (numbers in this section refer to Figure 3) allows the wheels to be adjusted along their centerline from a separation of a couple of inches to an overlap of about an inch. Since the groove in the wheels spirals, it is necessary for the wheels rotation to be exactly synchronized during overlapped operation. This is achieved by use of a timing belt drive. A variable speed drive control (2) allows variance in the surface speed of the wheels and therefore metal removal rate (also

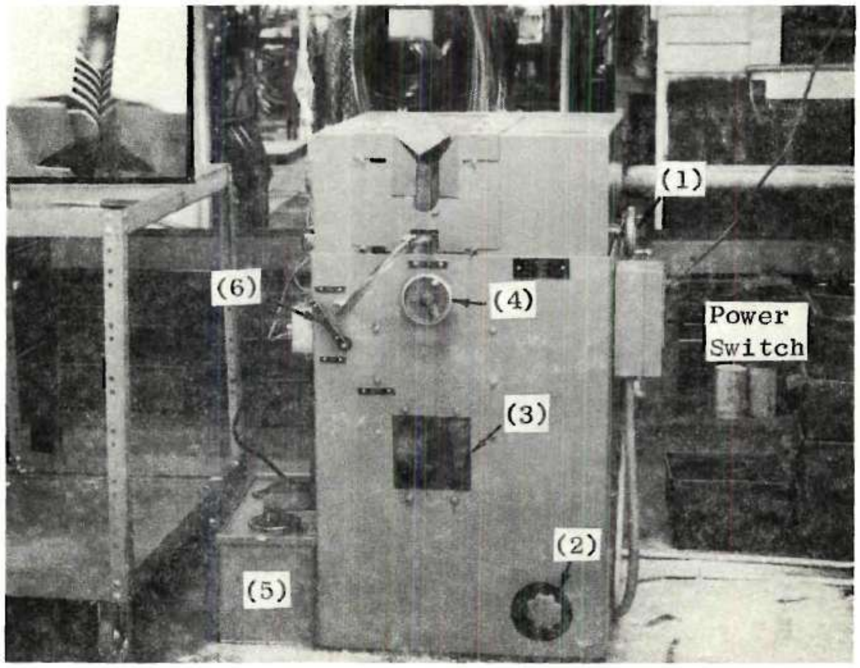


Figure 3. Nicholas Edge Grinding Machine. Insert is Detail View of Abrasive Wheel Configuration, Arrows Indicate Wheel Rotation. Numbers Refer to Discussion in Text.

quality of the edge finish). In the coarse edging operation, wheel speed is not as important as in the final edge finishing which was done on the second machine. The spiral grooves of this machine have a further advantage, they prevent grooving of the knive edge since the wheel surface "travels" along the knife (when the knife is held stationary).

Wheel dressing is particularly critical with this type of wheel configuration. An integral dressing system (3), (4) is provided to insure accurate control.

Cooling, lubrication, and flushing is provided by a light oil circulating system. The primary advantage of oil is the improvement in the edge finish that is obtained over that obtained with water. The system consists of a reservoir (5) in which a submerged pump is placed. Oil can be fed to the top of the abrasive wheels or to the wheel dressing system; the lever (6) controls the feed rate as well as feed location.

Multi-purpose Knife Tester

The basic configuration of the knife testing machine was designed by Mr. N. A. Milone of the University of Michigan for a study of the dulling characteristics of various cutting boards on knife edges. Mr. Milone graciously provided plans for the apparatus which was then constructed by Southern Saw Service, Inc. As experimentation began it was found that some major modifications were needed for the machine to meet the requirements of this study. By comparing Figures 4, 5, 6 and 7 with Mr. Milone's sketch of his machine (included in the Appendix), the modifications are quite evident.

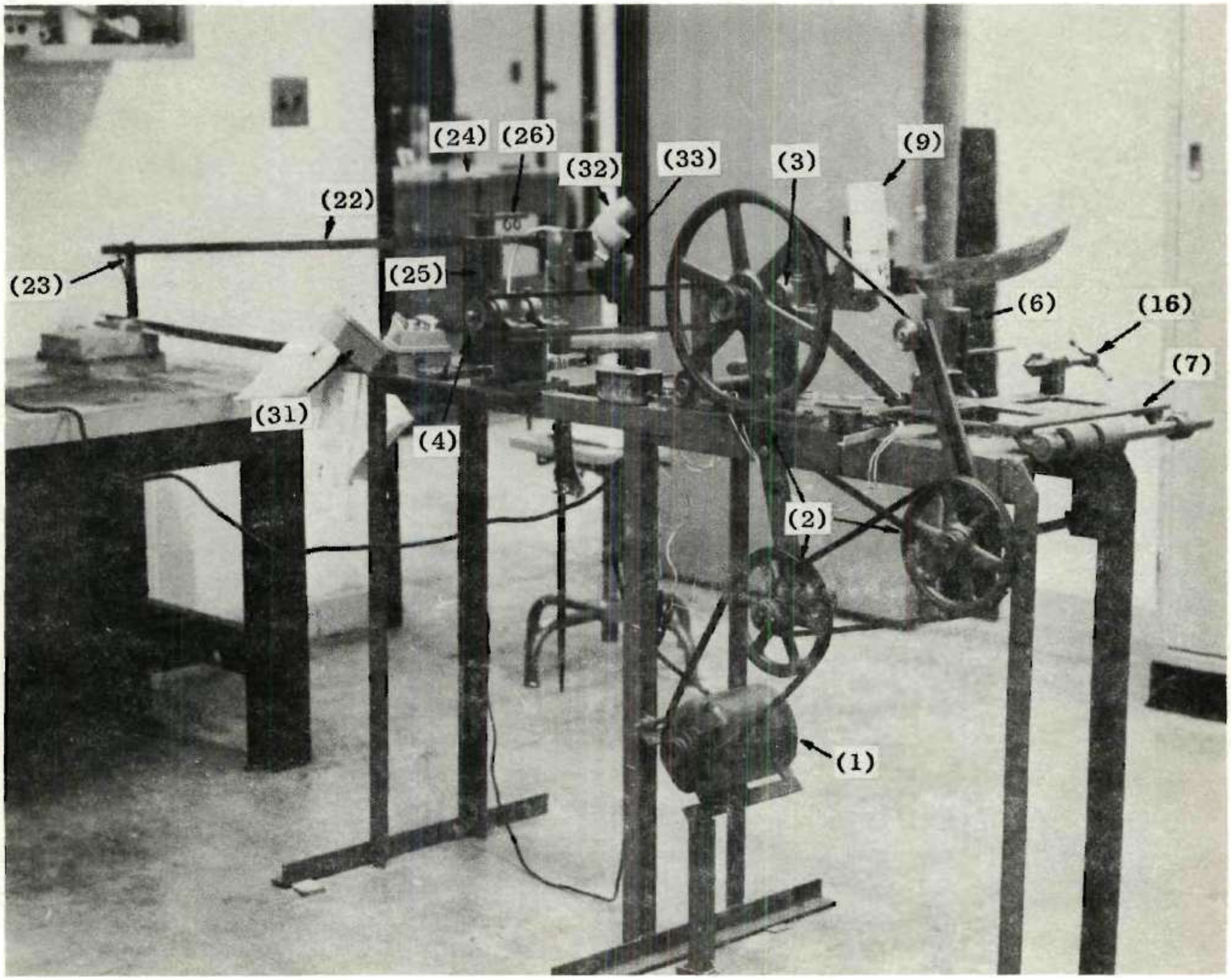


Figure 4. Backside View of Multi-Purpose Knife Testing Machine. Numbers Refer to Discussion in Text.

The knife testing machine was the principal device used in the tests conducted on the knife specimens. Systematic dulling of the knife edges was accomplished on the knife dulling section of the machine. The progress of the dulling of the knife edge was followed by sharpness measurements made with the sharpness testing section of the machine. The knife blades' ability to penetrate a material was also evaluated with the aid of the machine. The dulling section provided the necessary control of the knife stroke length and pressure.

General Construction

The machine has three basic systems: the drive system, the knife dulling section, and the sharpness testing section. The drive system provides speed reduction from 1725 revolutions per minute to about one revolution every three to four seconds. The reduced speed is supplied to the two drive cams, one in the knife dulling section, the other in the sharpness testing section by a set of V-belts.

The support structure of the machine was of 36 inch angle iron legs welded to a 14 inch steel plate on which the function mechanisms were mounted. The machine was driven by a 110 volt A.C., one-sixth horsepower motor (1) through a V-belt and pulley speed reduction linkage (2) (numbers in these sections refer to Figures 4, 5, 6, and 7). The final speed gives one revolution every three to four seconds at points (3) and (4).

The shaft at point (3) provides power to a cam for driving the knife testing portion of the machine. The shaft at point (4) provides power to the cam for the sharpness testing portion of the machine.

Knife Dulling Arrangement

The knife specimens were dulled by stroking them against a bone. Meat market research showed that the severest general usage of the knife was encountered during "boning." Boning is the removal of the meat from the associated bone. Due to the desire to duplicate meat market conditions in the experimental tests and to have a realistic dulling rate of the knife edge, bone was chosen as the dulling medium. The selection of the particular bone to be used is discussed in a later section.

The dulling section afforded constant stroke length for the knife edge to cut into the bone, and control over the pressure of the knife edge against the bone. An associated mechanism moved the bone so that each cut was made into a fresh area of the bone, thereby eliminating the effect of a cut into an old groove.

At various intervals of dulling, the knives were tested for sharpness on the sharpness testing section. A cycle counter attached to this section recorded the number of dulling strokes in the interval.

The cam connected to the shaft at point (3) provides drive to the knife holder (5) and to the ratchet (6), for the moving table (7), through a drive lever (8). The knife holder (5) is a simple screw clamp into which the knife handle may be inserted. Connected to the knife holder is a post for holding weights (8). These weights allow control of the pressure between the knife edge and the dulling machine.

The cam also drives a lever linkage (8) to a ratchet (6). The ratchet (6) provides synchronized movement of the dulling medium (10), in this study a bone, by moving the table (7) along a screw (11), on which the bone is mounted in another screw type vise (16). The movement

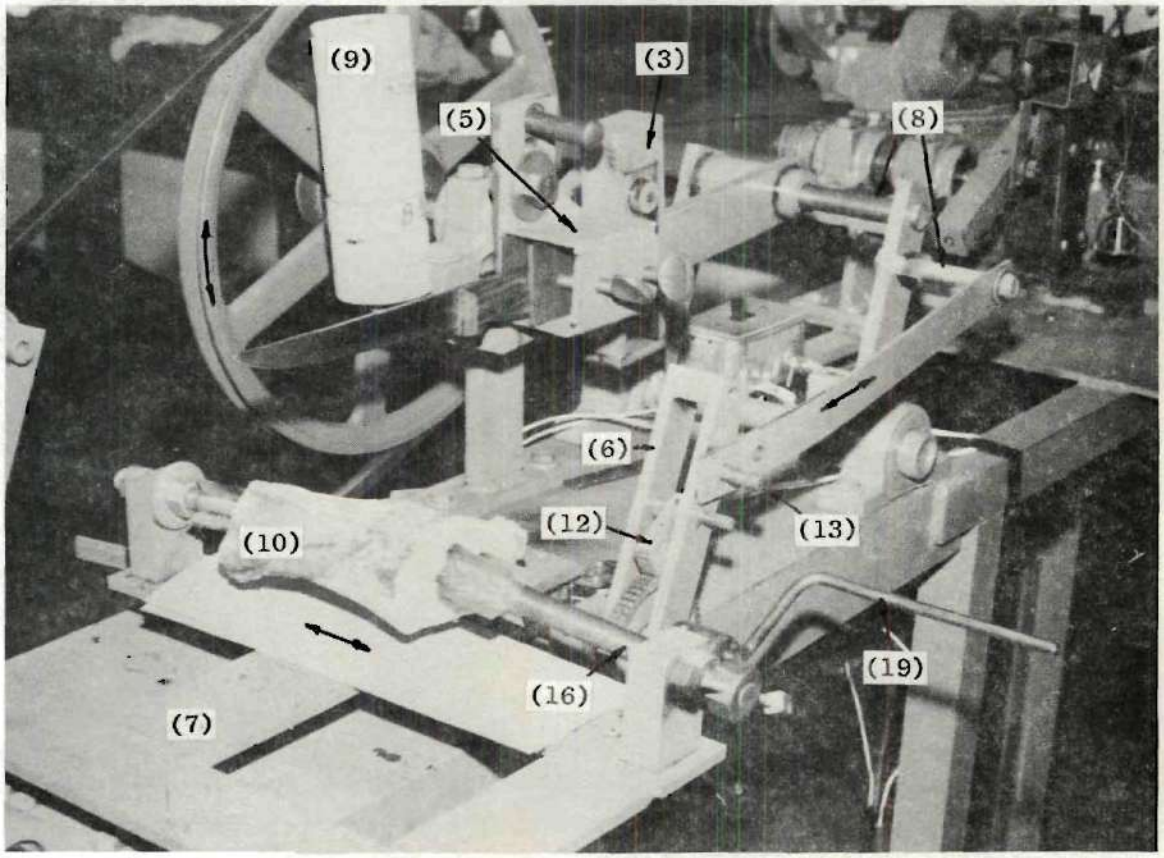


Figure 5. Detail of Knife Dulling Section of Multi-Purpose Knife Testing Machine. Arrows Indicate Motion of Associated Mechanism. Numbers Refer to Discussion in Text.

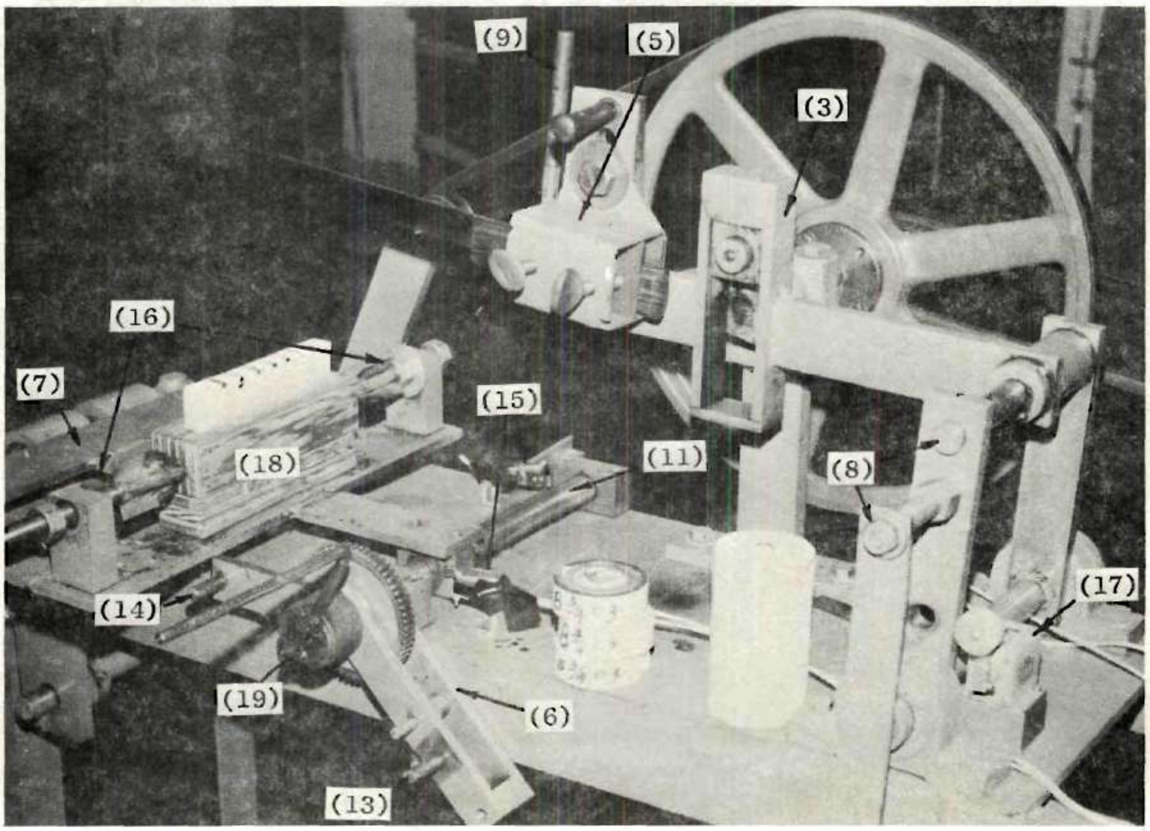


Figure 6. Detail of Cutting Penetrability Test Setup on Knife Dulling Section of Multi-Purpose Knife Testing Machine. Arrows Indicate Motion of Associated Mechanism. Numbers Refer to Discussion in Text.

of the table may be reversed by reversing the ratchet tongue (12) and the table synchronized with the knife motion by moving the linkage arm from pin (13) to pin (14). The movements must be synchronized so that the table moves when the knife is in the air and when the knife is in contact with the bone the table is at rest. Limit switches (15) were installed to turn off the machine when the end of travel of the table was reached. This allowed semi-automatic operation of the machine. An integral cycle counter (17) was mounted adjacent to the drive lever to record cycles of the drive (number of knife strokes).

Cutting Penetrability Arrangement

The cutting penetrability experiments established the knife blade's ability to cut into a material. The knife was allowed to make a single cut into a block of paraffin. The machine gave a constant stroke length and control of the cutting pressure. Since the cutting stroke, pressure, and medium were constant, or known, the depth of the cut penetration could be related to the knife specimen's thickness and cutting angle.

Cutting penetrability experiments were carried out on the dulling section of the machine after several adjustments were made. The ratchet drive was disconnected from the cam at the ratchet pins (13) or (14), and a paraffin block holder (18) was put in place of the bone. Rapid movement of the table (7) was obtained by use of a crank (19) connected to the drive screw (11). Otherwise all functions of this section of the machine were unchanged.

Sharpness Testing Section

Since there is no established sharpness standard, a reproducible measure had to be devised. Mr. Milone used the cutting of a thread to measure sharpness. After several experiments to check this method, it was found to be sufficiently sensitive and reproducible to be used in this study. The method is, however, not absolute, so as a relative standard the sharpness of each undulled knife was obtained and used as a base for comparing the sharpness of the dulled knives.

Sharpness, in this study, is defined as the number of strokes required to cut a standard thread under a given tension level.

The sharpness testing portion of the machine provided constant conditions for measuring the number of strokes required to cut the thread. The machine did this by giving a set cutting stroke by the knife, simple and exact adjustment of the knife blade in relation to the thread, and simple variance of the thread tension.

The shaft at point (4) connects to the cam (2) for eccentric drive of the knife holder (21) for this section of the machine. The knife handle is clamped in the holder by thumb screws, as in the dulling section knife holder. The tip of the knife blade is connected to an extension arm, (22) which is supported in a saddle (25) by a small "C"-clamp. The extension arm is about four feet long (the extension arm smooths the motion of the knife and makes for simpler alignment for testing).

A screw (24) elevates the thread holding boom (26) in the support mast (25). Two eye hooks (27) hold the thread (29) from which a weight pan (28) is suspended. The eye hooks have smooth V-notches cut in them to keep the thread from riding up the sides of the eyelets during contact with the knife edge.

The weight pan is attached to the thread by a modified alligator clip (30). Varying weights may be placed on the pan to adjust the tension in the thread. A macroscope (32) and light source (33) were attached to this section in order to optically follow the condition of the knife edge during dulling.

This multi-purpose machine permitted the dulling of the edges of the knife specimens in a rigidly controlled environment. The length of the dulling stroke against the bone was constant, as was the load, or pressure, of the knife against the bone. The ratchet drive to the moving table allowed the knife to make a fresh cut into the bone on each stroke, since the table, and therefore the bone, moved a fixed distance on each cycle. The limit switches and the cycle counter permitted semi-automatic operation, so that constant attention was not required.

The features of constant load and length of stroke permitted reliable reproduction of the cutting penetrability tests.

The sharpness testing section provided an excellent standard for determining the relative sharpness of the dulled and undulled knives. With this equipment the length of the knife stroke against the thread was exact and the thread tension was completely controlled.

Bending Tester

The bending tests primarily measured the materials' toughness as a function of material hardness and thickness. An early study of knives

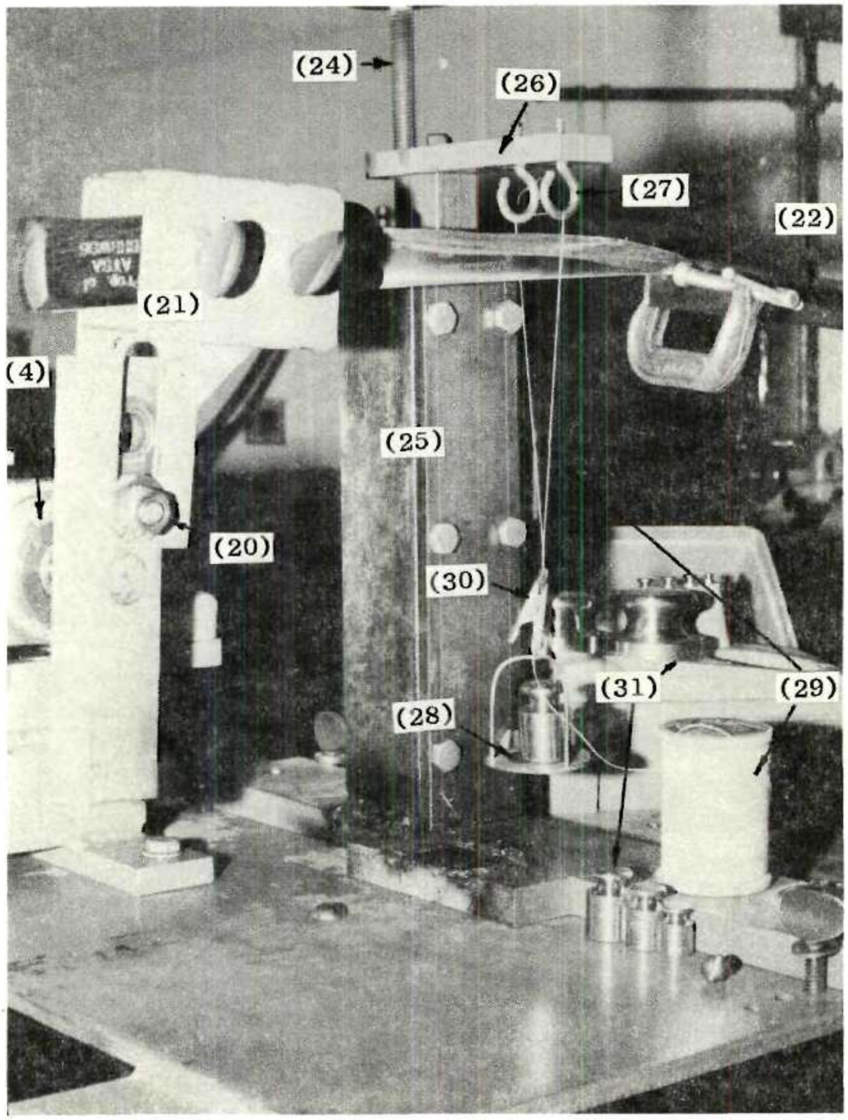


Figure 7. Detail of Sharpness Testing Section of Multi-Purpose Knife Testing Machine. Numbers Refer to Discussion in Text.

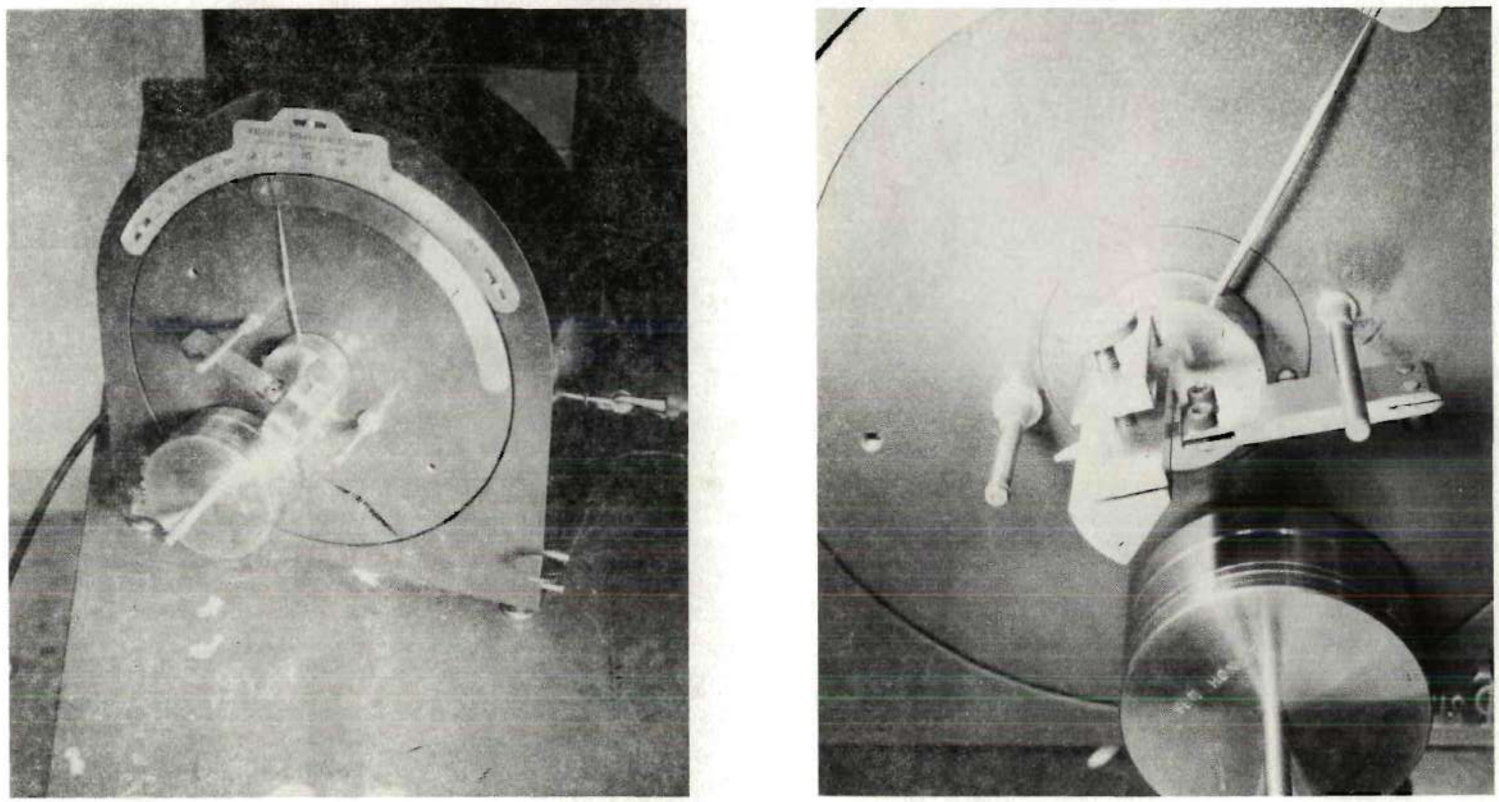
that failed in market usage showed that breakage and bending of the edge was the main factor in early termination of the knife's lifetime.

A standard tensile test would not truly duplicate the loading encountered by the edge, so stress-strain curves were obtained for the bending mode. The stress distribution within a material under a pure tensile load is quite different from the stress distribution found in the same specimen under a bending load. In normal usage a knife edge will never be placed under a pure tensile load, but rather under a bending load.

The bending tester, used to evaluate the knife materials' mechanical properties, was a 50 inch-pound Tinius-Olsen Stiffness Tester. This instrument was chosen so as to increase the thickness range of the material that could be tested.

The machine loads the specimen at a fixed, constant rate by rotating it against the free "floating" load. The angular relationship between the specimen and the load allows any desired percentage of the load to be applied, up to 100 per cent.

From the machine readings of per cent load applied by the machine and the deflection of the specimen from the zero load position, a stress-strain curve under a bending load is obtained. Depending on the load applied and the material strength, the specimen may be bent to fracture or to a set load and the permanent set or plastic deflection may be measured.



(a) (b)

Figure 8. Tinius-Olsen Stiffness Tester, (a) General View, (b) Detail of Specimen Mounting and Loading Mode. Arrows Indicate Direction of Motion of Associated Part.

CHAPTER III

EXPERIMENTAL PROCEDURE

All of the knives used in this study were made of 440C stainless steel. High carbon plain carbon steel and some tool steels are also commonly used for knife blades, but 440C is the most popular selection for meat market cutlery. This popularity is primarily due to the corrosion resistance of stainless steel which is necessary in sanitary environments. In addition to stainless' corrosion resistance, it is relatively easily formed into a finished product.

The problem was resolved into four basic experiments (listed in order to importance, discussed in order of performance). The first set of experiments consisted of establishing the dulling characteristics of an array of knives of the same hardness but differing edge angles and thickness at the edge. Three knives at each of seven different angles from about 10 degrees to 84 degrees were ground to different thicknesses at the edge. The thinnest knife was about .012 inch thick at the edge, the medium knife about .020 inch, and the thickest about .040 inch.

The second experiment used the same array of knives as in the previous experiment. In this test each knife made one stroke at five different pressure levels into a block of paraffin. The depth of the blade's penetration into the paraffin block established each blade's ability to penetrate a medium.

The third test was a measure of material strength. Knife blanks of 440C stainless steel in the hardened, untempered condition were obtained. The blanks were given various tempers, and bending specimens of various hardnesses and thickness were machined. The specimens were bent in a stiffness tester and stress-strain curves were plotted.

After data from the previous three experiments were analyzed, the fourth experiment was conducted. In this test knives of higher hardness were ground at angles and thicknesses in the vicinity of the optimum configuration obtained from the analysis of the data from the previous experiments. In this way the effect of material hardness on the dulling characteristics was evaluated and in turn the optimum configuration and properties for a knife blade made of 440C stainless steel was determined.

Knife Sharpening Procedure

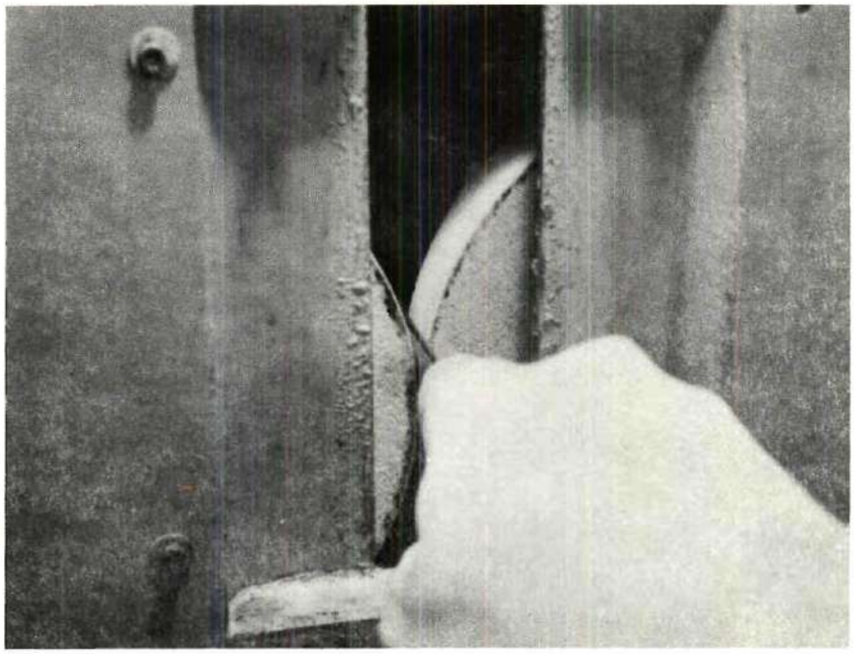
The knives used in the first experiment were previously shaped, polished and handles affixed by the knife maker that supplies Southern Saw Service. The knives used in the fourth experiment were blanks, still coated with quenching salts. Since the first one half inch of the leading edge is the area being studied, the grinding procedures for both sets of knives were the same. To clarify this point, it should be noted that the knives supplied by the knife maker are tapered, in thickness from the back of the blade to the cutting edge and from the handle to the tip of the blade. All of the blades used in this study were hollow ground to a predetermined thickness at the edge. Since the hollow grinding usually extends back from the edge about one half inch, and it is this area which the study focuses on--the taper or lack of taper on the remainder of the blade is not important. This means that no special preparation was required in preparing the knife specimens from the hardened blade blanks.

Hollow Grinding

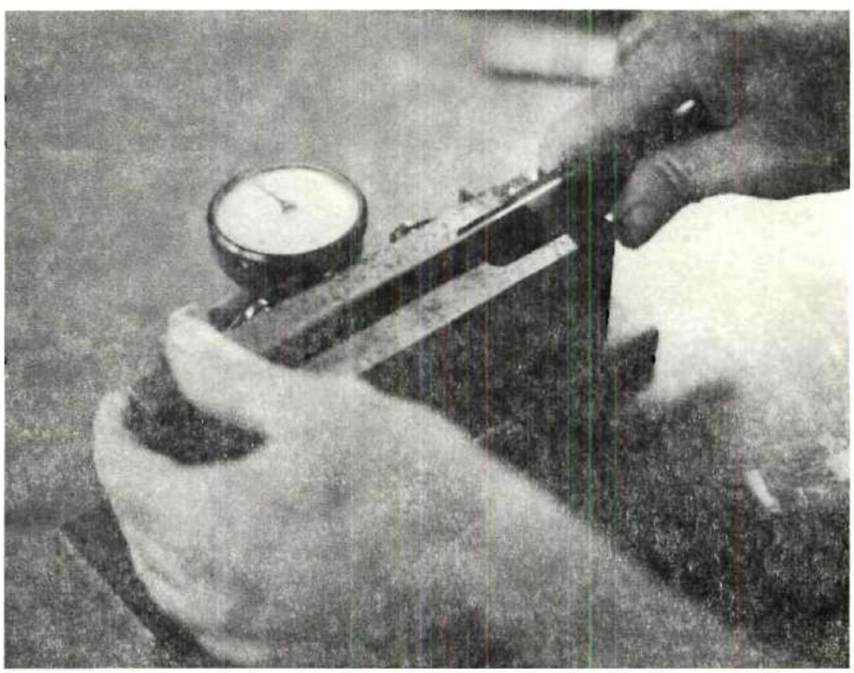
Each knife was passed through the grinding wheels with special care being taken to maintain a feed rate fast enough to prevent overheating of the blade and yet slow enough to obtain a satisfactory material removal rate. Of particular interest was maintaining the knife at 90 degrees to the centerline of the wheels. An even hollow grind is essential if the edge angle is to be symmetrical about the vertical centerline of the knife. The thickness of the edge was frequently checked with the edge thickness tester in order to follow the progress of the operation. When the desired thickness was reached, about .012 inch for the thin blades, .020 inch for the medium blades, and .040 inch for the thick blades, the knives were ready for the edge forming operation.

Edge Grinding

The next step was the coarse forming of the cutting angle. After every other pass, the edge was observed under a macroscope. When the taper of the angle came to a point, the coarse forming was terminated. Visual inspection of the grinding process also allowed immediate correction of asymmetric grinding. The seven angles ground on the experimental knives were 11.5, 26, 47, 54, 59.5, 80, and 84 degrees. The optimum cutting edge angle was expected to lie between 30 and 60 degrees. In order to cover the range, it was desired to grind angles at 30, 45, 55, and 60 degrees. At this stage of the investigation, the means of

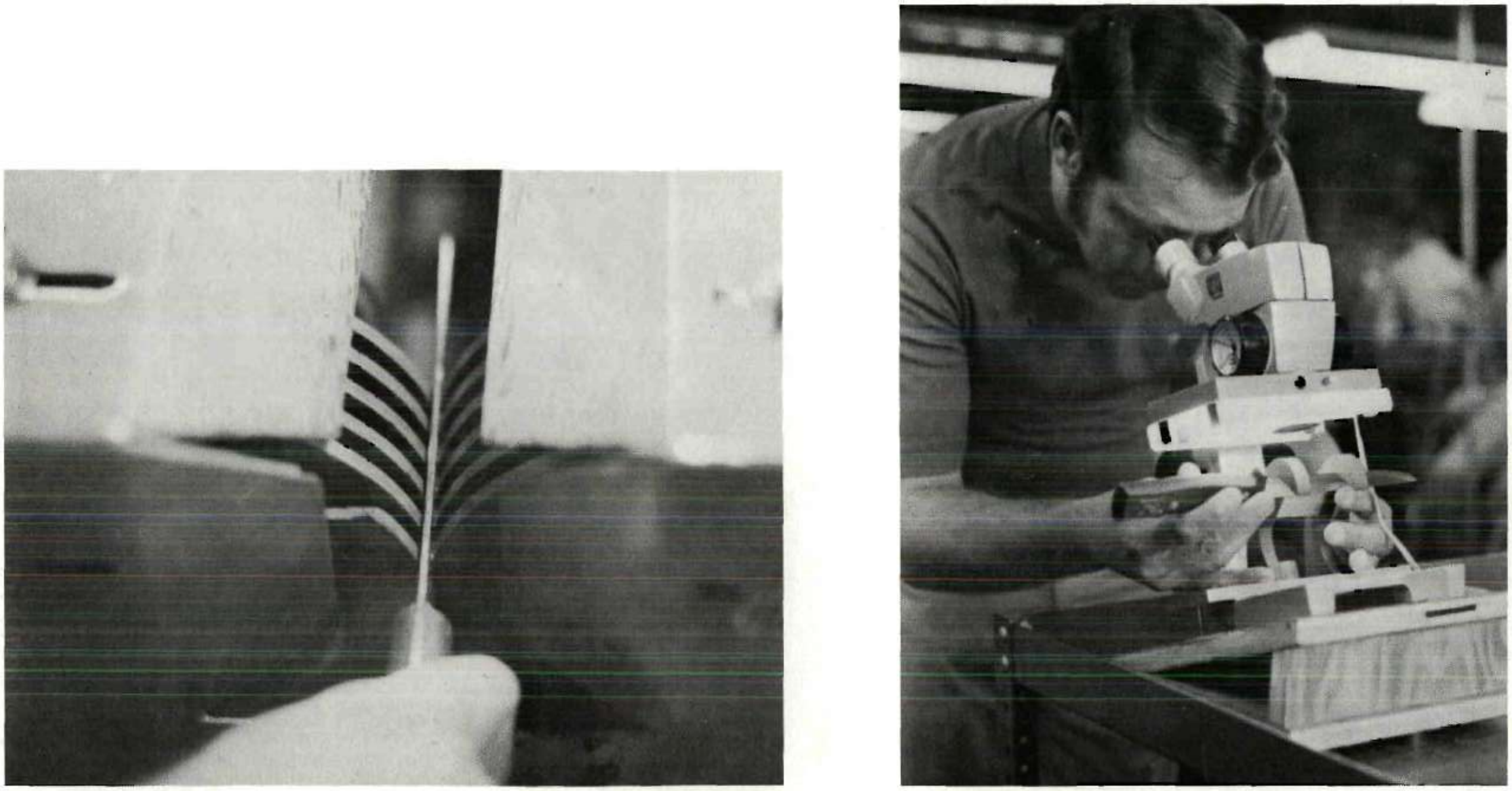


(a)



(b)

Figure 9. Steps Involved in Hollow Grinding Knives: (a) Hollow Grinding the Blade, (b) Checking Thickness at the Edge of the Blade.



(a) (b)

Figure 10. Steps Involved in Edge Forming and Finishing: (a) Grinding the Edge, (b) Optical Inspection of the Edging Progress.

measuring the cutting edge angle were rather crude, and hence, there was a difference between the experimental and the desired angles. The 11.5, 80, and 84 degree edge angles were ground in order to establish the end points of the range of cutting edge angles. With each angle a blank strip of steel was also ground for later mounting and exact measurement of the angle ground on the knives. The exact edge angles were measured on a photomacrograph of the steel blanks ground with each edge angle.

The final step in the edge grinding was done on a set of 400 grit abrasive wheels. The wheels were set to duplicate the angles ground by the coarse edging machine. This alignment was checked under the macroscope. By observing the superposition of the abrasive marks from the two edging machines, the coincidence of the two machines could be made exact. The knife was passed through the final edger until the resultant edge finish met the requirements discussed in the chapter on results.

Knife Testing Experiments

Cutting Penetrability Tests

The first experiment to be run was that of cutting penetrability. It was run first so that the later dulling experiments would not affect the results here. If these experiments were run later, then the knife edges would have been dull and/or distorted from dulling, and the results would not be truly representative of a good, sharp edge.

Paraffin Test Block Preparation. The blocks of paraffin used in the penetrability tests were one half inch thick, four and nine-sixteenths inches long, and two and one-quarter inches wide. The paraffin was a commercially pure grade. The liquid paraffin was cast at ninety degrees Centigrade into an ice chilled, dry, aluminum mold. The mold was made in three pieces (two lipped sides which fitted to a side form) and held together with rubber bands (see Figure 11). The liquid paraffin was held at the casting temperature for 24 hours to allow the lighter fractions of the paraffin to evaporate, thereby insuring greater homogeneity (paraffin is a mixture of several heavy hydrocarbons).

In preparation for casting, the mold was placed in a copper trough and packed in ice. The liquid paraffin was then poured, to fill the mold. Ice water was then added to the trough to increase the thermal conduction from the mold. As the paraffin contracted (due to the cooling and solidification) more liquid was added to the mold. When the mold was about 80 per cent filled with solid paraffin, the mold was again filled and the top was sealed by passing an ice cube over the surface. The sealed mold was then submerged in a bucket of ice and water to complete the solidification. After the mold was cooled it was opened, the paraffin block was removed and placed on a shelf to cure and equilibrate to room temperature.

These exacting procedures were necessary because of the extremely variable physical properties of paraffins. The blocks were allowed to sit for one week prior to their use in the penetrability tests.

Penetrability Test Procedure. A holder for the paraffin blocks was constructed of three-quarter inch plywood (see Figure 6. (18)). The holder permitted rigid positioning of the paraffin slab on the moving table of the dulling section of the multi-purpose knife testing machine. The ratchet drive was disconnected from the eccentric drive; table movement, when needed, was obtained with the rapid advance crank connected to the table drive screw (see Figure 6. (19) and (11), respectively).

The weights were removed from the post connected to the knife holder (see Figure 6. (9)). The knife was clamped in the holder. The paraffin block was positioned so the knife would make a cut into the block about three quarters of an inch from the end of the block. The machine was turned on, and the knife was allowed to make one full stroke. The block was advanced about three-quarters of an inch, a weight was added to the post, and another stroke was made into the block. This continued until either the block was used up or the maximum weight was reached.

When the test was completed, the block was removed from the holder by the vertical edges so the indentations were not disturbed. The knives were carefully cleaned with kerosene in preparation for the dulling tests which followed. The paraffin blocks were next prepared for measurement of the indentation depth.

Indentation Depth Measurement. In order to make the measurement of the depth of the cut easier, each indentation was filled with black ink and allowed to set overnight (see Figure 11). The actual depth measurement was made with a Starrett Depth Micrometer. A Vickers Stereo Macroscope was used to observe the measurement. The measurements were made with an accuracy of .001 inch.

Knife Dulling Procedure

The knife to be dulled was securely clamped in the knife holder (see Figure 5. (5)) of the dulling section of the multi-purpose knife

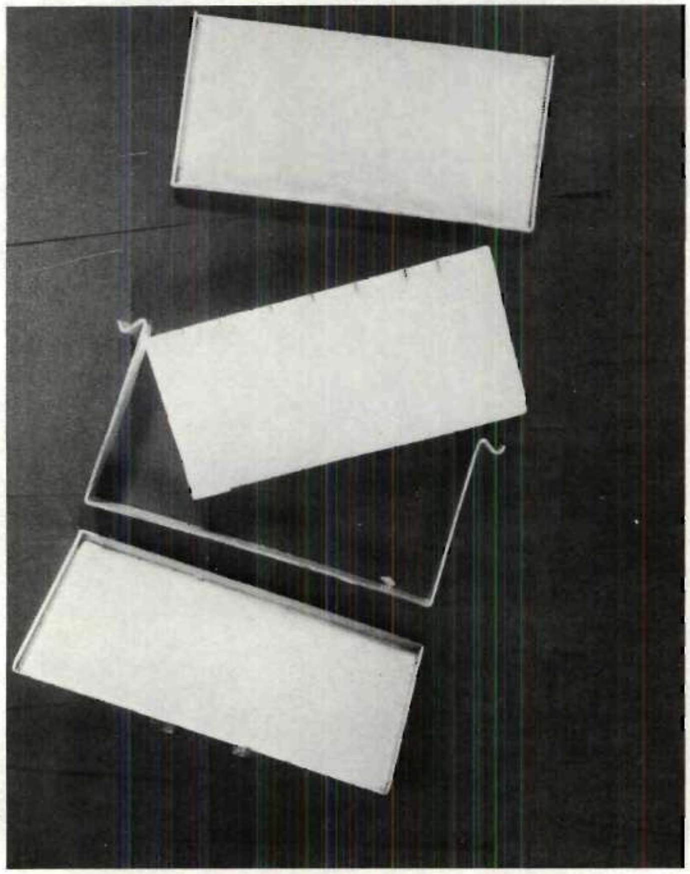


Figure 11. Paraffin Casting Mold and Paraffin Test Block Prepared for Measurement of Penetration Depth.

testing machine. The desired amount of weight was placed on the knife holder weight post (see Figure 5. (9)). A freshly prepared bone was securely clamped onto the moving table.

The preparation of the bone for usage in the knife dulling portion of the machine was quite systematic. The bone was received from Greene's Grocery Store in just the condition they had finished with it. The hip socket end of the bone was free, the shaft portion of the bone was more or less cut clean of meat. The portion of the bone toward the knee joint was still joined to the lower leg bone's upper segment. The center section of the upper thigh bone was the desired section because of its regular cylindrical shape. The most regularly shaped eight inch section (the length that fit into the holder on the moving table) was selected and the two end joints of the bone were cut off. The center section of the bone was then wrapped in two layers of water moistened paper towels and sealed in a plastic bag. The bags were then placed in a refrigerator for storage until usage.

Next the limit switches were set so the machine would turn off when the end of the bone was reached (see Figure 6. (5)). The limit switches prevented the knife from striking the steel clamps that hold the bone in place on the moving table, and permitted unattended operation of the machine. The bone was positioned so that the knife began cutting at one end. The ratchet was then connected to the drive lever at the correct pin for synchronized motion of the table with the knife, and the ratchet tongue adjusted for correct movement of the table (see Figure 5. (6), (8), (7), and (12), respectively). Finally, the cycle counter (see Figure 6. (17)) was set to zero and the machine started.

All of the knives were dulled at the maximum machine load. This provided a force of 96 ounces between the knife and the bone. This force level is the practical upper limit of the force normally exerted by a butcher on the knife during boning.

The machine was stopped when either a particular number of dulling strokes were completed or when the end of the bone was reached and the limit switch deactivated the machine. At this point either the knive was removed from the machine for sharpness testing, or the bone was rotated to a fresh surface, the ratchet readjusted, and dulling continued.

If the knife was to be tested for sharpness, then the ratchet was disconnected from the drive lever so the table would not be moved while the sharpness testing section of the machine was being used.

Sharpness Testing Procedure

The sharpness of each knife was tested prior to any dulling, and at various points during the dulling process. Each time the knife was to be tested for sharpness, the edge was carefully cleaned with kerosene.

To test the sharpness of the cutting edge the knife was securely clamped in the knife holder of the sharpness testing section (see Figure 7. (21)). The tip of the knife blade was then clamped to the extension arm (see Figure 7. (22)). Minor adjustments in the blade position were then made so that the section of the edge being tested was centered with the notches in the string eyelets, (see Figure 7. (27)) and so that the edge being tested was very close to horizontal when the eccentric drive was at the top of its cycle.

The thread (Coats & Clarke # 40 Mercerized white cotton) was fed off the supply spool and through the support eyelets. The weight pan (see Figure 7. (28)) was then attached to the loose ends and the thread placed in the V-notches (this was actually just a check, since the notches were at the lowest point of the eyelets and the thread fell into them naturally).

The thread support boom (see Figure 7. (26)) was then lowered until the thread just touched the knife edge when the eccentric drive was at the top of its cycle. The machine was next momentarily activated to move the knife away from the thread. The thread support boom elevating screw (see Figure 7. (24)) was then turned two full revolutions to lower the thread. This reduction in height of the thread above the knife edge was just enough for the weight hanging from the thread to be fully supported by the knife edge when the eccentric was at the top of its cycle.

After the cycle counter had been set to zero, the machine was switched on. When the thread was cut in two the machine was cut off and the cycles required to cut the thread were noted. Usually the test began with the greatest weight on the pan and after several tests at each weight, the weight on the string was reduced until just the weight of the pan was left.

By plotting the number of dulling strokes given the edge versus the sharpness of the edge (as in Figure 13, for example) a measure of the knife's dulling rate is readily obtained. Changes in dulling rate can be related to physical changes in the cutting edge. These changes are easily observed under a low power microscope. If the knife is tested to complete dullness (to be discussed later) then the useful life of the knife is portrayed by its dulling curve of number of dulling strokes versus sharpness.

Bending Test Procedure

The bending tests were performed in order to obtain information on the knife material's strength as a function of hardness and thickness. Specimens were prepared at six hardnesses with four thicknesses at each hardness.

Specimen Preparation

A dozen quenched, untempered knife blanks of 440C stainless steel were obtained from the supplier. The blanks had hardnesses of 58 to 60 Rockwell "C."

It was desired to have specimens spanning the range from Rockwell "C" 60, the maximum hardness, down to Rockwell "C" 54, the lowest hardness used in present day cutlery. The untempered knife blanks were first stress relieved at $300^{\circ}F$ for one hour. At this point the hardness was checked and the blanks that were to be cut into specimens for the Rockwell "C" 60, 59, and 58 samples were selected and set aside. The blanks that were to be used for the Rockwell "C" 57, 55, and 54 samples were then tempered in a salt bath (see Appendix for discussion of heat treatment of 440C stainless steel). The heat treated and tempered blanks were next cut into sections about one-quarter inch wide and about two inches long (the length was in the rolling direction). The sectioning of the blanks was accomplished on a Buehler Cutoff Machine using a thin sectioning wheel and a modified coolant system to insure against over heating.

The width of the specimens varied widely, therefore it was necessary to correct the specimens to a uniform width. To accomplish this, the samples were collectively stacked on edge on a flat surface and ground to the same width. The grinding was done on a Brown and Sharpe #5 Surface Grinder that was equipped with a magnetic check. Both edges of the samples were ground to make both the finish and the width uniform.

The specimens were then thinned to thickness of .080, .040, .020, and .010 inch. The specimens were about .082 inch thick prior to the thinning. In order to insure uniformity and freedom from distortion, half the thickness that had to be removed was taken from each surface of the specimen. In reducing the sample to the desired thickness each surface was alternately ground. Several specimens of each thickness were prepared for each material hardness. The thinning was done on the same surface grinder with a material removal rate of .00025 inch per pass. Due to the small size of the specimens the magnetic chuck would not hold them in place, individually. Therefore, the specimens were glued to a ground, tool steel plate with Eastman 910 Adhesive. The extremely low grinding rate was necessitated by two factors. First, even though the grinding surface was flushed with coolant (water and soluble oil), the specimens could not be heated; otherwise a softening would inevitably occur. And second, the shear force of the wheel against the specimen was close to the adhesion strength of the Eastman 910 adhesive. A less important problem was associated with overheating; the thermal shock involved caused the adhesive to rupture. The specimens were easily freed from the tool steel slab by a light tap to the edge of the specimen (the adhesive was quite brittle when cured) or they could be boiled off in N,N-Dimethyl Sulfoxide, or N-N-Dimethyl formamide. Both methods were tried and the tap off method was chosen.

The specimens were then cleaned in N-N-Dimethyl formamide, re-cleaned in carbon tetrachloride, and demagnetized.

Bending Test Procedure

The bending tests were performed on a 50 inch-pound Tinius-Olsen Stiffness Tester. The specimen was clamped into a specially designed tool steel extension (see Figure 8 to clarify discussion). The extensions provided with the machine were not rigid enough for the thicker specimens. The remainer of the specimen was inserted into the vice clamp on the machine. The gap between the extension clamp and the vise was set at twice the thickness of the specimen being bent.

The machine load was established on a trial bend of each thickness. The .080 inch specimens required a 50 inch-pound load, the .040 inch specimens 20 inch-pounds, the .020 inch specimens 10 inch-pounds, and the .010 specimens 4 inch-pounds. The trial specimen also established the increments at which data was to be recorded.

After the specimens were tested in the bending machine, two further pieces of data were collected from them. First, the thickness of each of the specimens in the vicinity of the test was measured with a conical point micrometer. Second, the hardness of the specimens was measured with a Riehle 136 degree diamond pyramid, or Vickers, hardness tester. The same indenting load, 10 kilograms, was used on all specimens regardless of the thickness.

The bending tests supplied stress-strain curves from which the yield point and or point of fracture could be determined. The thickness and hardness measurements supplied the remaining information necessary for complete analysis of the bending test data.

CHAPTER IV

DISCUSSION OF RESULTS

Knife Dulling Experiments

Knife dulling experiments established the relationship between dulling rate, or sharpness retention, the physical configuration (cutting angle and edge thickness) of the knife blade, and the hardness of the blade material. In evaluating the worth of the results of this test, two factors were scrutinized: 1) the medium chosen for dulling and 2) the method of measuring sharpness.

Factors Affecting the Meaning of the Results

Choice of Dulling Medium. Routine service brings the knife edge into contact with several substances: the cutting board, meat, gristle, twine, and bones. In considering which of the previously mentioned items would be used as the dulling medium, the following factors were considered: would the dulling rate be realistic, would the expense be prohibitive, and how easy would it be to handle the material.

The use of meat or gristle was not feasible because of the expense and their extremely low dulling rate. Twine and similar substances were deleted since the per cent of usage time for cutting such items was negligible. This left two possibilities, the cutting board and the bone. In order to choose between the two, several meat market surveys were conducted. As a result of the butcher's opinions and observations of knife usage, the bone was chosen as the dulling medium.

The investigation revealed that a great deal of work was done on the cutting board, but it can be observed that the toughest work for the knife was encountered during boning. Boning is the operation wherein the bulk of the meat is removed from the large bones. In this removal process, the cutting edge encounters meat of all toughnesses, gristle, and the bone. The knife-bone contacts are frequent and severe. The knife-cutting board contacts are made at lower pressure levels and therefore not as severe. The cutting board material is usually a hard wood or a wood product. The wood cutting boards tend to be softer and less homogeneous than bone. These factors make the choice of bone as the dulling medium sufficiently attractive, but there was one other consideration. In the beginning of this study, the role of corrosion in knife dulling was unknown. By using bones the juices and acids of the meat were present along with the bone material itself, a situation that could not be easily duplicated with a cutting board.

The primary focus of this set of experiments was on just what happens to the cutting edge of the blade during usage. Therefore, it was necessary for the actual dulling process to affect the cutting edge alone, or as little of the rest of the knife as possible. In order to meet this constraint, the knife was made to initiate a fresh cut into the bone on each dulling stroke. If the edge were to reenter an old cut, the primary forces on the edge would be frictional and they would be directed toward the sides of the blade and the taper of the edge angle, and not against the cutting edge.

An associated effect turned out to be of importance. The fresh cut should be independent of the old cut. In other words, the fresh cut should be far enough away from the previous cut that the bone between the cuts retains its integrity. This constraint is important because of the large, immeasurable forces on the sides of the cutting edge which are present if the constraint is relaxed, the knife edge tends to be bent to one side and broken off. Although this type of dulling does occur in some cases, the majority of the time a virgin cut is made on each stroke. Since the forces involved in dependent dulling strokes are so ill defined, the simpler independent dulling stroke scheme was used. This requirement was met by mounting the bone on the screw movement, ratchet driven table so that on each cycle the bone was moved just enough for the knife to initiate a fresh cut on each stroke.

The next problem was that of deciding which bone to use. The requirements were that the bone be easily obtained, of a useful length, and very close to cylindrical (for the even force distribution afforded by a perpendicular cut into the bone surface). The bone that met these conditions was the center section of the upper thigh of the cow. Greene's Grocery very kindly provided these bones whenever they were needed.

As previously mentioned, the bone provided the environment of meat without the cost of the meat. This was possible because, naturally, not all the meat was removed during boning and also the bone marrow secreted juices. These characteristics immediately gave rise to two questions: 1) what effect does drying of the bone have on dulling rate, and 2) how does the amount of meat, fat, gristle, etc. left on the bone affect the dulling rate.

The dulling rate was found to vary with the dryness of the bone. A dry bone dulled the knife faster than a fresh bone. This dependence appears to be primarily a function of lubrication. The fats and oils in the fresh bones reduced the friction during the cutting stroke, whereas in a dry bone the fats and oils are devoid of plasticizing moisture and form a hard abrasive crust. Under normal circumstances the knife edge never encounters a dry bone, therefore, only fresh bones were used. The bones were obtained from the butcher the same day the meat was removed from them. Freshness of the bone was insured by storage in plastic bags in a refrigerator. The bones were never kept over a total of one and one-half weeks and never used again after three days' exposure to normal room environment. These time limits standardized the results with respect to changes in bone texture with time.

The texture of the bone itself was a function of the amount of meat, fat, and gristle left on the bone as well as the freshness of the bone. The previously mentioned precautions eliminated concern over freshness. The amount of meat, fat, and gristle left on the bone was always small, seldom over one-quarter inch thick, most frequently less than one-sixteenth inch thick. The thickest layers always consisted of fat, the thinnest of meat and gristle. The dulling effect of all these components was negligible compared with that of the bone. The main factor affected by these components was lubrication of the cut. As long as the bone was in the "fresh condition" (as defined by the time limits previously discussed), the dulling characteristics of the bone were unaffected by meat, fat, and gristle coverings.

<u>Evaluation of Sharpness Standard.</u> Previously, it was pointed out that there was no standard measure of sharpness presently established. The concept of sharpness is complicated by the large number of factors, i.e., the material being cut, the manner in which it is cut, friction between the sides of the cutting implement and the material already cut, etc. Another consideration is related to the manner of expressing sharpness in units. There appears to be no logical set of units in which an absolute measure of sharpness could be expressed, as contrasted to properties such as hardness or material deformation, which can be expressed in kilograms per square millimeter, or centimeters per centimeter, respectively.

Since an absolute expression of sharpness was unavailable, a relative measure of the property was adopted. The sharpness test required was one that would measure the sharpness of the cutting edge alone. Several "energy absorbed in cutting" type tests were considered, but each contained a large dependence on the rest of the blade. The final choice was a test of the blade's ability to cut through a fiber. Milones' method of measuring relative sharpness[1,2] meets the requirements set forth above, in addition to the obvious requirements that the test be reproducible and reliable.

Several fibers were tried and rejected in favor of the final choice, cotton. Both stranded and monofilament polymers of nylon, rayon, and saran were examined. The major portion of the polymers strength appears to be in a very tough surface layer. Once the surface layer is notched, the fiber is very easily broken. This led to a threshold behavior. Below a certain fiber tension an extremely large number of cutting strokes were required to sever the fiber and above that tension there was insufficient sensitivity to the knife sharpness. Similar experiments on cotton fibers showed a much wider sensitivity range to different knife sharpnesses. A Coats & Clark # 40 Mercerized white cotton thread was chosen as the standard fiber for the sharpness tests.

Each time the knife was mounted in position for sharpness testing, the section of the blade to be tested was very carefully aligned, as described in the chapter on experimental procedure. This alignment was necessary for two reasons. First, by being sure that the section to be tested was horizontal at the top of the cycle, the length of the cutting stroke (the length of the edge that actually made contact with the fiber) was easily duplicated. Second, by standardizing the height relationship of the thread relative to the knife (as described in the chapter on experimental procedure), the thread tension was accurately reflected at the knife edge during the period the edge was in contact with the fiber.

Each test of the sharpness of the knife edge consisted of determining the number of strokes necessary to cut the thread at various tension levels, the thread tension was varied from the weight of the pan plus fifty grams to the nominal weight of the weight pan. As was noted in the experimental procedure, the number of strokes required to cut the thread was recorded at the tension levels of 1) weight of pan plus fifty grams (the pan weighed twenty grams), 2) weight of pan plus thirty grams, 3) weight of pan plus twenty grams, 4) weight of pan plus ten grams, and 5) the nominal pan weight.

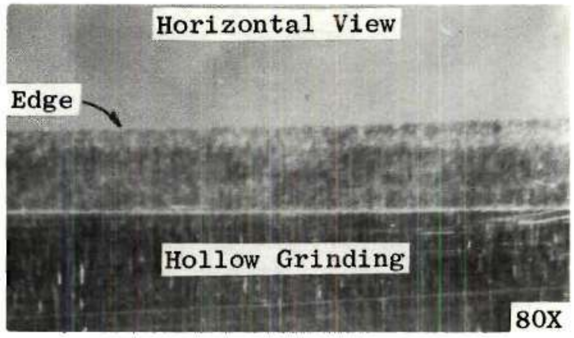
The dulling curves (plots of number of dulling strokes versus number of strokes required to cut the thread) obtained with low thread tensions were different from the curves at the higher tensions. At low tensions (weight of pan and weight of pan plus ten grams) the test was extremely sensitive to the condition of the cutting edge. The sharpness that this tension level measured was a true knife edge sharpness, but its practical significance was small. The sharpness levels measured at this tension are on the same scale as razor blade sharpness. A dull razor blade is still sufficiently sharp to do an excellent job in meat cutting. The ideal, of course, is to make a knife that can maintain this sharpness level. The problem is that the comparative abuse a knife edge receives, as opposed to a razor blade's usage, requires a stouter edge, and, therefore, some compromise in the sharpness level has to be expected. As the thread tension is increased, the effect of the condition of the very edge of the cutting edge is reduced. At low tensions the thread "skips" from prominence to prominence, only a small portion of the edge is actually in cutting contact with the thread. As the tension is increased, the thread ceases the skipping and more closely follows the contour of the edge. If the tension is increased, further still, the tensile strength of the thread is approached and the test loses its sensitivity. All the thread tension levels were used in the tests that follow.

Optical Sharpness Standards

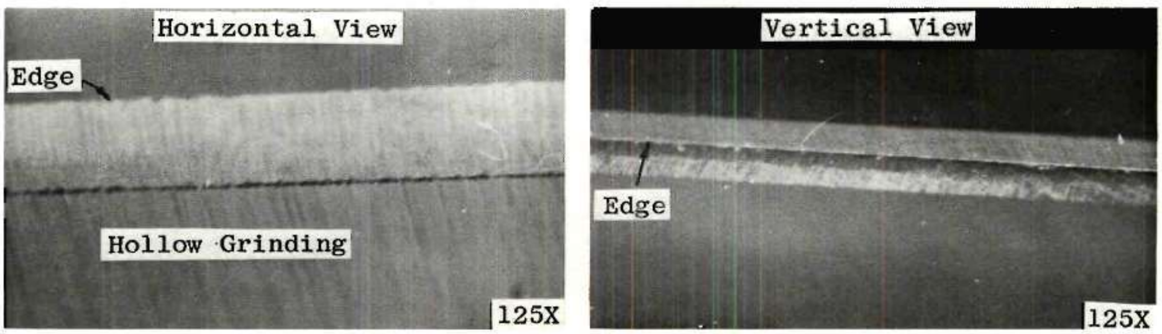
During the course of this study a large number of knives were observed under the stereo macroscope at powers varying from ten to fifty times magnification (the terms used in this discussion are illustrated by the macrographs incluced in Figures 12, 22, and 23). From these observations it became evident that knife edges considered to be sharp had several characteristics in common, and that dull knives lacked one or more of these characteristics. Several hundred knives in assorted stages of sharpness and dullness were studied to establish a systematic optical evaluation of sharpness. With the aid of a professional cutlery sharpener, Mr. T. Maestranzi of Maestranzi Brothers, Inc. in Chicago, Illinois, the optical evaluation technique was checked against three standards being used at present in the cutlery industry.

The three techniques being used are as follows: 1) The knife is drawn, with minimum force, through a sheet of note paper (about a 10 pound weight paper). A dull section of the blade shows up as an unclean cut, the paper is not cleanly severed but slightly torn apart. The knife is considered sharp when the whole blade produces a smooth clean cut through the paper. 2) The edge is considered sharp if it will dry shave (no lubrication present) the hair from the arm. And 3) the system used by most master knife sharpeners, the thumb is lightly drawn along the sharpened edge. If the edge is sharp, the feeling sensation is one of the edge grabbing the thumb. (All of these techniques are extremely sensitive to a wide variety of variables and therefore useless in the hands of an inexperienced operator.)

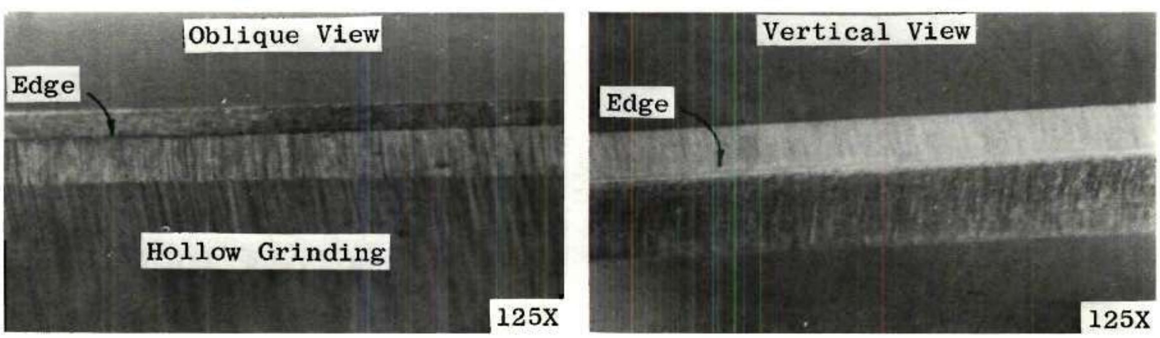
In each comparison test, the knife was optically inspected and the areas of sharpness and dullness were noted. The edge was then checked by each of the three above techniques by Mr. Maestranzi, who found identical areas of sharpness and dullness. The knives used in this test had cutting edge angles of about 25 degrees and 40 degrees.



(a)



(b)



(c)

Figure 12. Optical Indicators of Sharpness: (a) Small Edge Angle, (b) Medium Edge Angle, (c) Large Edge Angle.

Mr. Maestranzi was able to tell that there was a difference in the edge angle, and both knives were judged to be of equal sharpness.

Optical Indicators of Sharpness. The knife blade was inspected with a stereo macroscope (as in Figure 10. (b)) at a magnification of about thirty times. The edge taper was checked first to see if the edge angle taper was uniform on both sides of the knife edge; this is important if the blade is to cut straight. Next the grinding striations on the edge angle taper were checked for uniformity and smoothness over the whole taper of the edge angle on both sides of the knife. If the striations are irregular, then the edge will not be uniform and its sharpness will be poor. The edge itself was then inspected to be sure a wire edge --a thin foil of the blade material--does not remain attached to the edge (see Figure 22 and 23) and that the edge is otherwise uniform. The presence of a wire edge dramatically shortens the useful lifetime of the edge. The final check was made by turning the blade so that the view was directly down on the edge. If the edge is not sharp, a streak of reflected light can be seen along the edge; the narrower this streak of reflected light, the sharper the knife edge will be.

An optical evaluation such as this is fast, simple, and immune to the variables that affect the three previously discussed techniques. By preparing a standard against which an operator can compare, the experience requirement for using this method is minimized.

Results for Small Edge Angle Knives

Of the seven edge angles considered in this study, the 11.5 degree edge angle knife was considered to be typical of small edge angle knives. The extremely long slope of the taper of the cutting edge characterizes this class of edges. The larger edge angle knives were of three thicknesses at the edge, but due to the narrow angle of small edge angle knives, only one thickness could be ground. The previous statement should be taken in light of the technique for measuring thickness at the edge, discussed in the previous chapter, since the thickness, herein used, is the thickness of the blade .030 inch from the edge.

The small edge angle knives have a second characteristic which tends to be detrimental to the edge's lifetime. The long slope of the small angle edge greatly enhances the possibility of a wire edge being present, and, similarly, increases the difficulty involved in removing it from the edge. Once the wire edge has been removed, however, the finished edge that remains is almost as fragile as the wire edge that was removed. The edges obtainable on this class of knives are extremely sharp, but the durability of the edge is extremely low.

Relation of Dulling Curve to Edge Deterioration. The small angle knives were very carefully ground so that the wire edge was completely removed, and a regular uniform edge left on the blade. The blade was dulled as described in the experimental procedure and a dulling curve, number of dulling strokes versus sharpness at each of five thread tensions was constructed. Figure 13 is a typical dulling curve for small edge angle knives.

The knife edge was dulled until the number of strokes required to cut the thread, in the sharpness test, exceeded 100 for the pan weight tension and five strokes for the pan plus fifty gram tension. At this point, the knife was considered dull. (This limit was used in all tests, and was the result of information obtained during meat market surveys

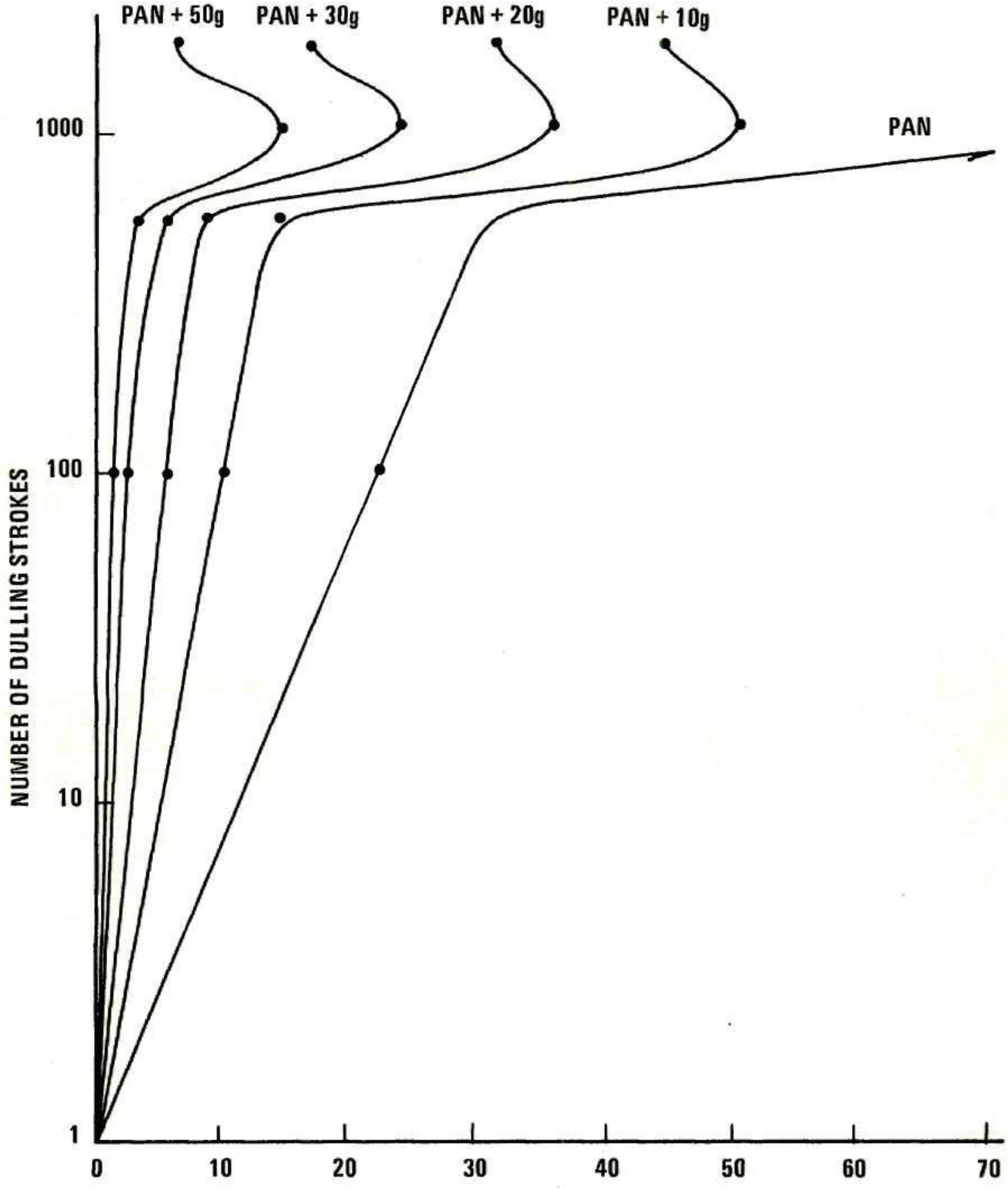


Figure 13. Typical Dulling Curve for Small Edge Angle Knives.

and preliminary knife preference tests.) As was pointed out earlier, the dulling of the edge was documented by the sharpness tests and by macroscopic observation of the edge.

During the first 500 dulling strokes, the edge remained uniform and regular. The dulling that occurred showed up as a slight broadening of the reflected streak of light from the edge (refer to discussion of sharpness test earlier in this chapter). However, over the next 500 dulling strokes the edge suffered severe deterioration. The edge became very ragged, in places the edge had folded slightly to one side, and in a few places the edge was "torn" from the rest of the blade. This type of deterioration was logically expected since the edge was extremely thin and therefore had less strength (to resist deformation) than the thicker region behind it.

The knife was dulled 1000 more strokes and again evaluated for sharpness. The deterioration observed at 1000 total strokes was worn away. In its place was an extremely irregular, fairly smooth edge. The sharpness was higher at the 2000 stroke level than at the 1000 stroke level, but this appeared to be due to the blade tearing the fibers of the thread apart rather than cutting them. A knife edge in this condition would not produce a quality meat product. The actual useful life of the edge was reached at about 600 or 700 dulling strokes.

<u>Results for Medium Edge Angle Knives</u>

The knives ground with medium edge angles are the class in which the optimum angle for the cutting edge was expected to fall. The angles in this group included 26, 47 and 54 degree edge angles. The taper length common to these and larger angles was short enough that a variety of blade thicknesses at the edge could be obtained. The three thicknesses that were aimed at for all knives were about .010 inch for the thin edge, about .020 for the medium edges, and .030 to .040 inch for the thick edged knives. There was a good deal of variance from the desired thicknesses for a variety of reasons none of which affect the results of the knife dulling tests (as will be seen later when the cutting penetrability results are discussed, this was an advantage rather than a hindrance).

As the cutting edge angle becomes larger, the possibility of a wire edge on the cutting edge becomes less likely. The 26 degree edge angle was on the border line, the initial edging produced a wire edge, but it was easily removed with little extra grinding. The 47 degree and larger edge angles did not have a wire edge present at any time during the grinding. This trend was to be expected because as the edge angle becomes larger, the taper of the angle becomes sharper. The more gentle the taper, the more pronounced will be the wire edge, whereas, when the taper is sharp, as in the larger angles, the edge comes rapidly to a point and a wire edge is less likely.

The dulling curves obtained for this group of knives revealed an important piece of information. The dulling curve for each edge angle is essentially independent of the blade thickness at the cutting edge. This lack of dependence on blade thickness at the edge is reasonable since the dulling mode did not require a deep penetration of the knife edge into the dulling medium.

<u>Dulling Curves for Medium Edge Angle Knives.</u> The dulling curves for the 26 degree edge angle knives were similar to the 11.5 degree edge

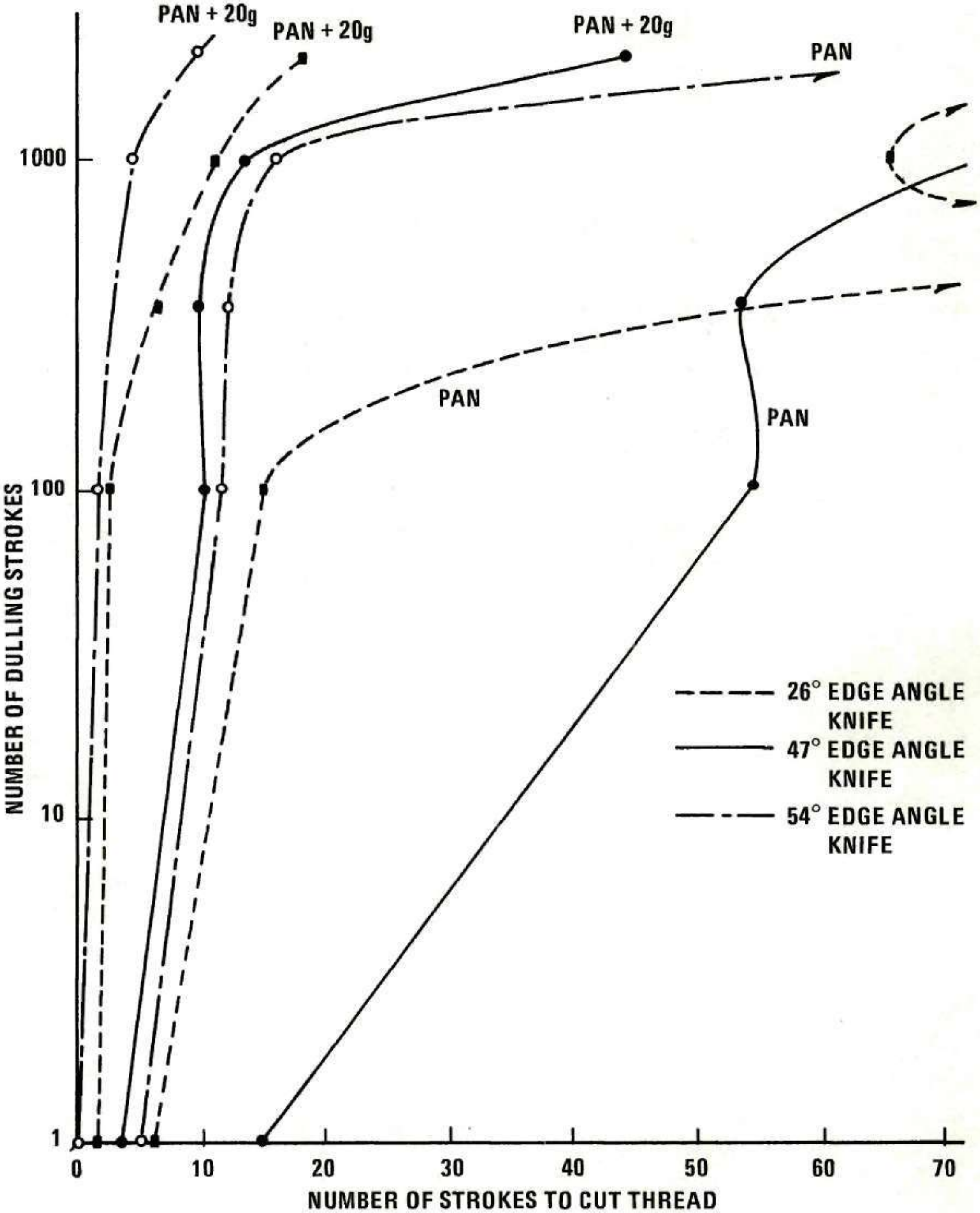


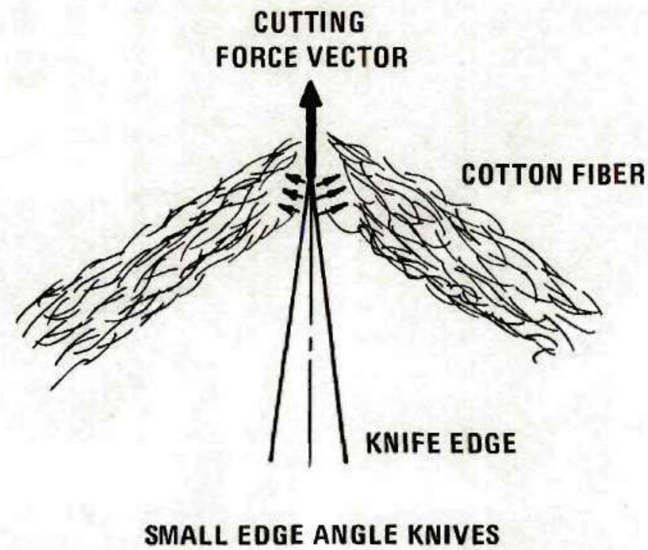
Figure 14. Typical Dulling Curve of Medium Edge Angle Knives.

angle knives, except that the peak moved out to 2000 total dulling strokes. The 26 degree edge angle knives, as mentioned before, were on the border line in terms of the existence of a wire edge. The physical condition of the edge followed the same trends as the 11.5 degree edge angle knives. The shift of the peak to about 2000 total dulling strokes means that the cutting edges lifetime is about 1000 strokes, an increase of almost two hundred per cent over the 11.5 degree edge angle knives.

The knives ground to edge angles of 47 and 54 degrees had a different type of dulling curve. The peak that corresponded to a deterioration of the cutting edge was absent. Figure 14 is a composite plot of the curves for the medium edge angle knives, the individual curves for each knife are included in the Appendix. None of the knives at these two edge angles showed the severe edge deterioration noted in the knives at the two smaller angles. The only sign of dulling was a broadening of the streak of reflected light at the edge (when viewed edge-on under the macroscope). Between 2000 and 5000 total dulling strokes, each knife's dulling curve begins to show an increase in dullness. This is the point at which the knife is at the end of its sharp lifetime, the extended life of the edge for these knives represents better than a fifty per cent increase in usefulness over the 26 degree edge angle knives.

Results for Large Edge Angle Knives

The large edge angle knives are the group of blades ground with edge angles of 59.5, 80, and 84 degrees. Although, all of the edges were sharp by the optical evaluation standards (discussed earlier in the chapter), the edges were extremely dull when tested on the sharpness



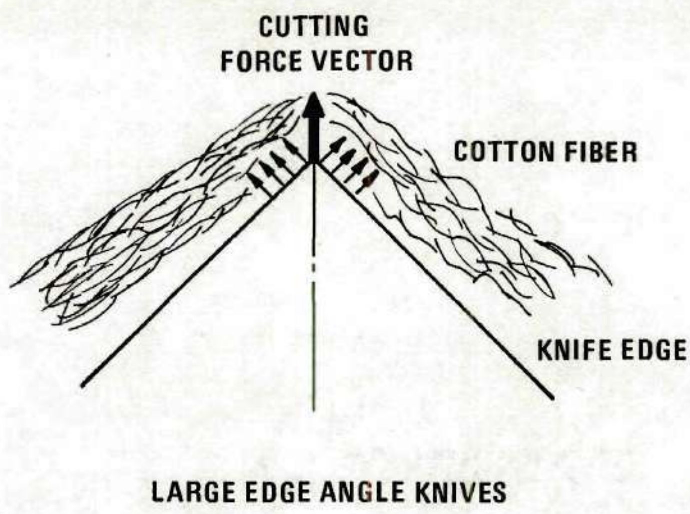


Figure 15. Diagramatic Explanation of Low Sharpness Readings for Large Edge Angle Knives.

tester. The three qualitative tests, previously discussed, were attempted and the edges did not perform nearly as well as the smaller edge angle blades.

The reason for this type of behavior is fairly reasonable. Reference to Figure 15 should aid in clarifying the following points. The fibers encountered by the cutting edge of the knife are not rigid in flexure or in diameter when a force is applied to them. This is true of meat (muscle fibers) and the thread (cotton fibers). When the fiber comes in contact with the knife edge, a certain amount of elastic deformation of the thread takes place. If attention is focused at the point of contact between the cutting edge and the fiber (as in Figure 15), it can be seen that the situation is reduced to one of force concentration. In the case of the small edge angles, the force level at the junction is extremely large (directionally) and also extremely localized. Whereas, in the case of large cutting edge angles, the forces are distributed over the whole surface of the cutting edge. The large force component, directed along the centerline of the knife cross section, that was present in the small edge angles is greatly reduced and diffused in the case of the large edge angles.

General Summary of Results of Knife Dulling Tests

The knife dulling tests established that the dulling rate of a cutting edge is primarily a function of the cutting edge angle and not dependent on the thickness of the blade at the cutting edge. This situation simplifies the analysis, in that the variable of edge thickness does not have to be considered further. The evaluation of the data was also simplified by the establishment of the upper and lower limiting edge angles.

The lower limit was absolutely set by the 11.5 degree edge angle knife. The dulling tests showed that the edge was just too fragile to stand up under the rough usage meted out in meat markets. The 26 degree edge angle knife can be considered the practical lower limit. This edge displayed the characteristics of both the small and medium edge angle knives. The edge was stronger, or tougher, than the edge of the smaller, edge angle knives, but the detrimental characteristics (deterioration of the thin edge) of the small edge angle knives still appear at a later stage in dulling.

The upper practical limit was set by the 59.5 degree edge angle knives. Knives with edge angles of 59.5 degrees and larger were unable to cut the thread (at a load of the weight pan plus fifty grams) in less than about 20 strokes, which is well outside the sharpness limits established. This left the edge angles from 26 degrees to about 54 degrees as possible optimized choices.

The optimum edge angle was ascertained by plotting the number of dulling strokes at which the edge began to become dull versus the edge angle in degrees. A curve was plotted in each of the five thread tension levels used for measuring the sharpness of the edges. This graph is presented in Figure 16. Each point represents the average "dull out" point for the knives of that particular edge angle, tested at the indicated thread tension level.

From Figure 16 it is immediately obvious that the best edge angle for the longest sharpness longevity occurs at about 45 degrees. The

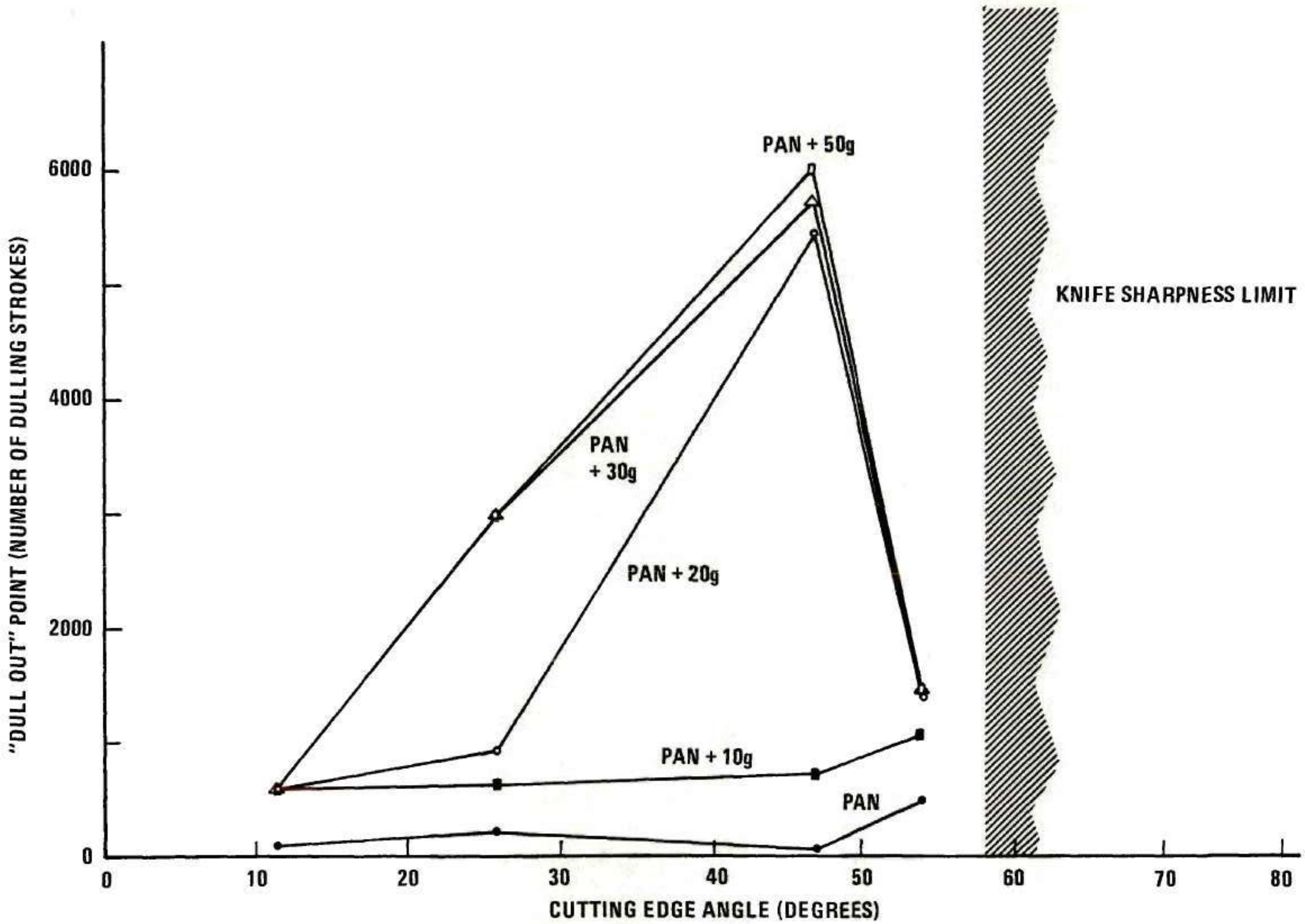


Figure 16. Cutting Edge Angle Optimization Curve.

peak in the curve is quite pronounced in this region. Considering the general shape of the curve (askewed toward the lower angles), edge angles from about 44 to 48 degrees can be considered approximately equivalent in their respective sharpness longevities.

Closer examination of the curves in Figure 16 reveals that there are basically two groupings of the curves: the curves for tensions of the pan and the pan plus ten grams, and the curves for tensions of the pan plus twenty grams, pan plus thirty grams, and pan plus fifty grams. In an earlier discussion of this method of sharpness testing, it was pointed out that the low tension levels allowed the thread to skip from prominence to prominence, not actually following the contour of the cutting edge. The fairly level curves in Figure 16 for the pan and pan plus ten grams tension provide added proof of this type of behavior.

The other three curves, having the higher tensions (Figure 16), are very closely grouped, except at the smaller edge angles. This variation in the grouping density is connected with the mode of the cutting edges' degradation. In the case of the larger edge angles, dulling is strictly a wear phenomenon. The larger edge angles have a great deal more mass at the cutting edge and therefore are tougher and less subject to the deformation dulling typical for the smaller edge angles.

The sharp drop off of the dulling point as the edge angle increases is further verification of the upper limit for useful edge angle values. This problem was previously discussed in the section on results for large edge angle knives.

The results presented in this particular section are for the group of knives designated as the first dulling experiment. The knives included in this group were of 440C stainless steel having an average hardness of Rockwell "C" 55 (occasional readings of Rockwell "C" 56 were found near the rear of the blade, and a few readings of Rockwell "C" 54 were found near the edge of the blade). From the data and analysis presented here, it can be concluded that for a knife made of 440C stainless steel having a hardness of Rockwell "C" 55, the optimum edge angle for maximum sharpness longevity should be between 44 and 48 degrees.

Earlier in this discussion, the possibility of corrosion from the meat juices affecting the dulling curves of the knives was suggested. An exploratory series of tests on 26 and 40 degree edge angle knives provided the answer. It was found that a knife could "become" sharper if allowed to stand for a period of time without having been carefully cleaned with solvents. The 40 degree angle edges were not affected as strongly as the 26 degree angle edges. The phenomenon did not become measurable in the 26 degree edge angle knives unless the standing period was of about one week's duration. The knives used in this study were allowed to stand overnight, at the longest, and no single series of tests on the same knife lasted more than three days. In this way corrosion effects on the dulling curves were minimized.

Effect of Material Hardness on Optimum Cutting Edge Angle

In order to investigate the effect of hardness on the optimum cutting edge angle, obtained in the previous dulling experiments, several knives of higher hardness were prepared. Eight of the hardened knife blanks obtained for the material strength tests that had a hardness of Rockwell "C" 60 were stress relieved for usage in this series of dulling experiments. As previously noted, the preparation of these samples was identical to the preparation of the knives used in the first series of dulling experiments. Angles of 26 degrees and 45 degrees were ground. The dulling technique for these tests were identical to those for the previous dulling experiments. Four knives at each of the two angles were prepared and tested. The thickness of the blade at the edge was .015 inch (after Figure 21).

The dulling curves for these higher hardness knives are presented in Figure 17 along with dulling curves for the 11.5 degree knife and the 47 degree edge angle knife, for purposes of comparison. As can be seen quite readily, the improvement in the sharpness longevity is dramatic. For the Rockwell "C" 55, the "dull out" point was less than 5,000 dulling strokes. For the Rockwell "C" 60 knives, the "dull out" point is in excess of 100,000 dulling strokes. The dulling curves for the Rockwell "C" 60 knives were carried to about 70,000 dulling strokes and no significant trend toward dullness was discovered. This indicates that extremely favorable effects on the sharpness longevity of the cutting edge may be obtained by raising the hardness of the blade material.

The curves for the Rockwell "C" 60 knife blades still show that the 45 degree edge angle has a better sharpness longevity than the 26 degree edge angle knives. This statement is based on the fact that the dulling curve for the 45 degree edge angle knives fell below the dulling curve of the 26 degree edge angle knives. This means that the dulling rate for the 45 degree edge angle knives was less than that for the 26 degree edge angle knives.

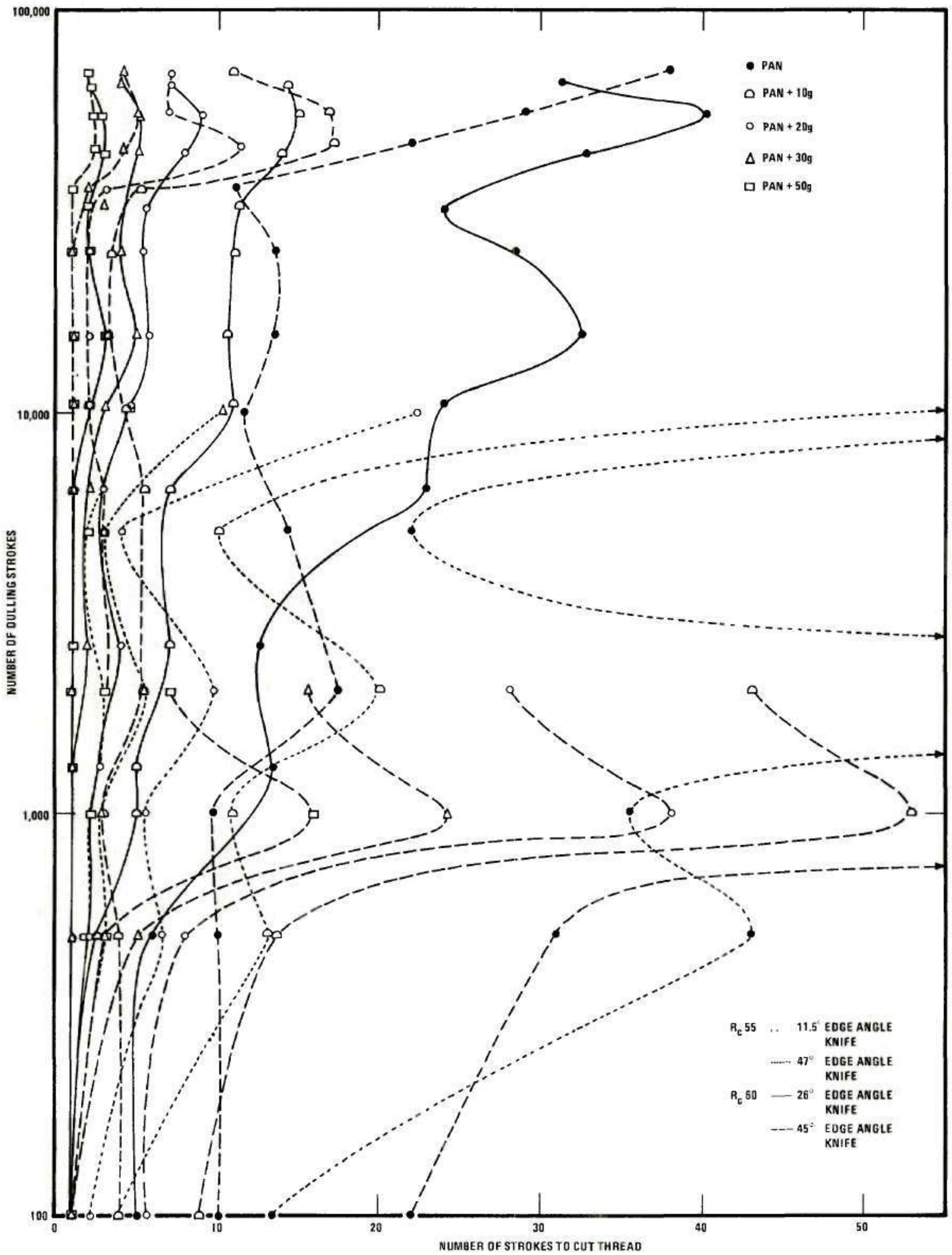


Figure 17. Effect of Material Hardness on Dulling Curve.

This experiment established that a knife material of higher hardness would yield great benefits in sharpness longevity. It further shows that if small edge angles are desired (angles less than the optimum), a proportional increase in their sharpness longevity can also be obtained.

Cutting Penetrability Results

The series of experiments measuring cutting penetrability were performed in order to evaluate the effect of the configuration of the leading edge of the blade on the knife's ability to penetrate a medium. It was expected that the results would, primarily, be a function of the thickness of the blade at the cutting edge, so, to be sure of this dependence, varying loads were employed in order to obtain deeper penetration so that the edge thickness effect could be more easily observed.

The factors affecting the penetration of one object into another are nearly as complex as the factors affecting sharpness. The most important factors are, of course in this study, the knife's leading edge configuration and the medium into which it is being forced. A third factor, which is almost as important, is the manner in which the blade is forced into the medium.

The configuration of the leading edge of the blade was the independent variable in these experiments and, therefore, not a problem, outside of actually preparing the edges. The third factor, mentioned above, was easily resolved. The knife dulling section of the multipurpose knife tester provided a controlled stroke length and stroke pressure for the knife's penetration of the medium. The motion of the machine was a reasonable facsimile of the motion of the knife when used by a butcher. These features assured a realistic means of bringing the knife blade in contact with the penetration medium.

Evaluation of Penetration Medium

The medium of concern at meat markets is meat in several forms. Utilizing meat as the penetration medium was infeasible for the following reasons: 1) meat is very expensive; 2) meat is extremely elastic under any force, therefore, a regular shaped block could not be maintained; and 3) once a cut or penetration has been made, there is no easy means of determining the depth of the cut. Because of these adverse properties, a substitute for meat had to be found.

The meat substitute had to be reasonably homogeneous, in order to obtain reproducible results. Secondly, the substitute had to be able to lubricate the cut in a manner similar to that of the meat's juices and fats. And last, the substitute had to maintain its integrity during and after the cut in such a way as to facilitate measurement of the penetration depth.

Justification of Paraffin as Penetration Medium. In addition to the requirement that the meat substitute be similar in properties, relative to the knife edge, to meat, the substitute should be inexpensive and easy to work with. After studying several alternatives, paraffin was chosen as the penetration medium.

Paraffin is fairly homogeneous even though it is a mixture of several heavy hydrocarbons. The procedure used for preparing the penetration test blocks insured a constant composition and the casting techniques insured a constant structure. Commercially pure paraffin (melting point of 52 degrees Centigrade) was easy to obtain and quite inexpensive. The material was very easy to handle in both the liquid and solid states.

Paraffin provided the lubrication needed to duplicate the juices of meats, as well as the rigidity needed during the cutting penetration. After the penetration the cut from the blade retained its shape and depth. Since the penetration marks were perpendicular to the surface of the test block, measurement of the cut depth was quite simple. Two questions about the use of paraffin should still be answered. First, is the lubrication provided by the paraffin really analogous to the situation encountered in meats? In order to answer this, a knife edge was cycled with a thin layer of paraffin adhering to the leading edge, and finally the blade was wetted with kerosene (an excellent solvent for paraffin) and cycled against the paraffin block. The depth of the penetratrations were the same in each case. This indicated that the paraffin was doing an adequate job of lubricating the cut, and that it was satisfactory as a meat substitute from the standpoint of lubrication.

The second question concerned the difference in the consistencies of meat and paraffin. Meat is soft, rubber-like, and very elastic, whereas, paraffin is harder and more rigid. The rigidity had to be present in order to have a reliable and reproducible test. Paraffin, although harder than meat, was the softest material that was found that met all the other requirements as a meat substitute as well as paraffin, the final choice was paraffin.

Penetrability Test Results

The data collected from these tests was plotted as depth of penetration versus load for each leading edge configuration (included in the Appendix). The data was then replotted as depth of penetration versus thickness at the edge (Figure 19) and depth of penetration versus cutting edge angle (Figure 18).

By comparing Figures 18 and 19, it can be seen that the depth of penetration of the edge is primarily a function of the thickness of the blade at the edge and that there is only a very slight dependence on the angle of the cutting edge. This fact is extremely meaningful since it shows that the two components of the leading edge configuration, the angle of the cutting edge and the thickness of the blade at the edge, can be separately optimized.

The results of this cutting penetrability test, however, cannot stand alone. The curves in Figure 19 are continually decreasing with increasing thickness at the edge. The problem is that, as the edge becomes thinner, it also becomes weaker and more susceptible to breakage. This penetrability test established the upper end point of blade thickness; a material strength test had to be employed to determine the lower end point.

A good knife edge should be capable of easily penetrating the medium which is to be cut by the knife. Figure 19 shows that as the knife edge becomes thicker, the penetration ability of the edge falls off. This characteristic establishes the need for a thin blade at the cutting edge. It is obvious, however, that the edge can only attain a minimum thinness, because the blade will become more susceptible to

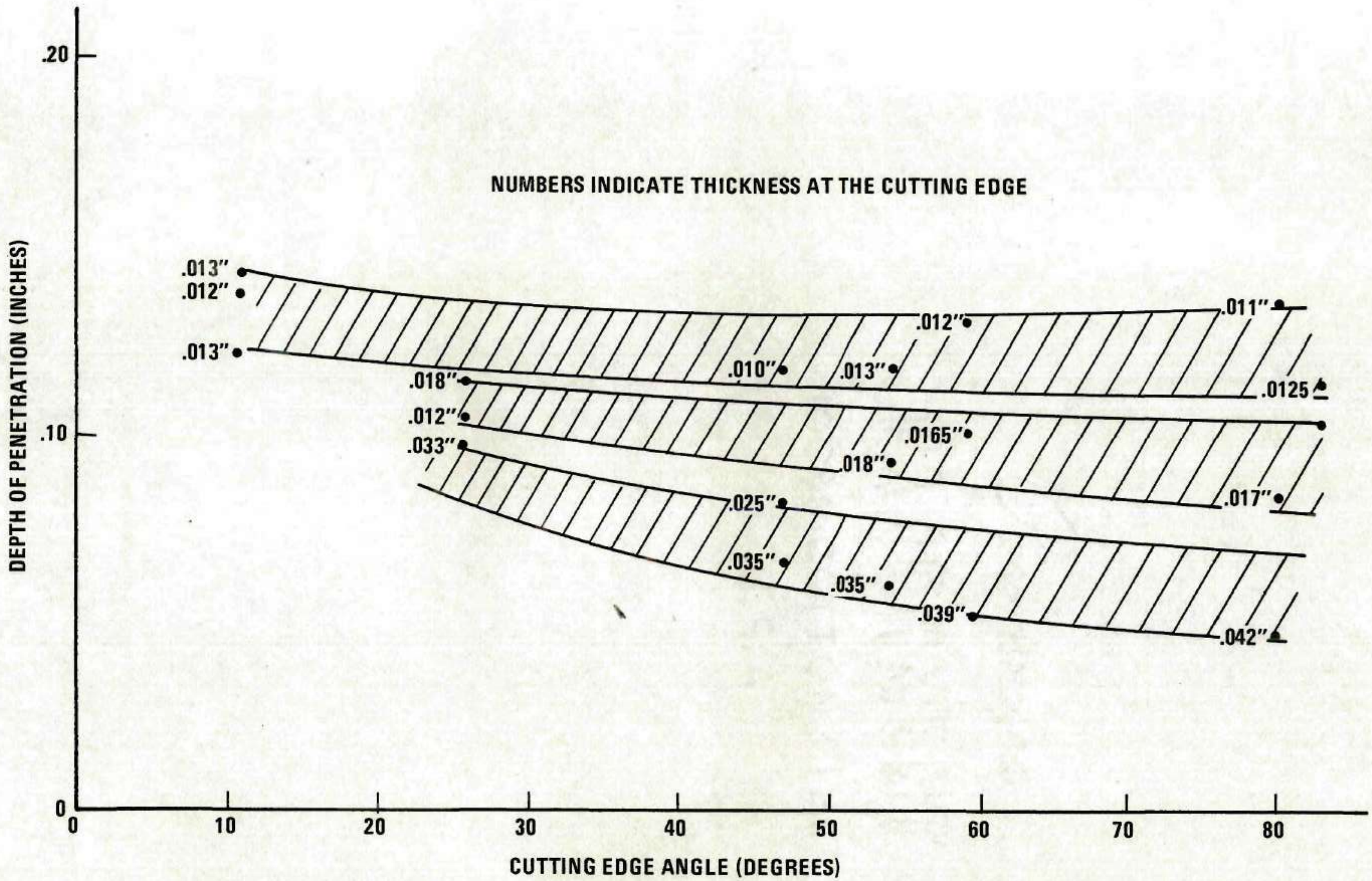


Figure 18. Dependence of Penetration Depth on Cutting Edge Angle.

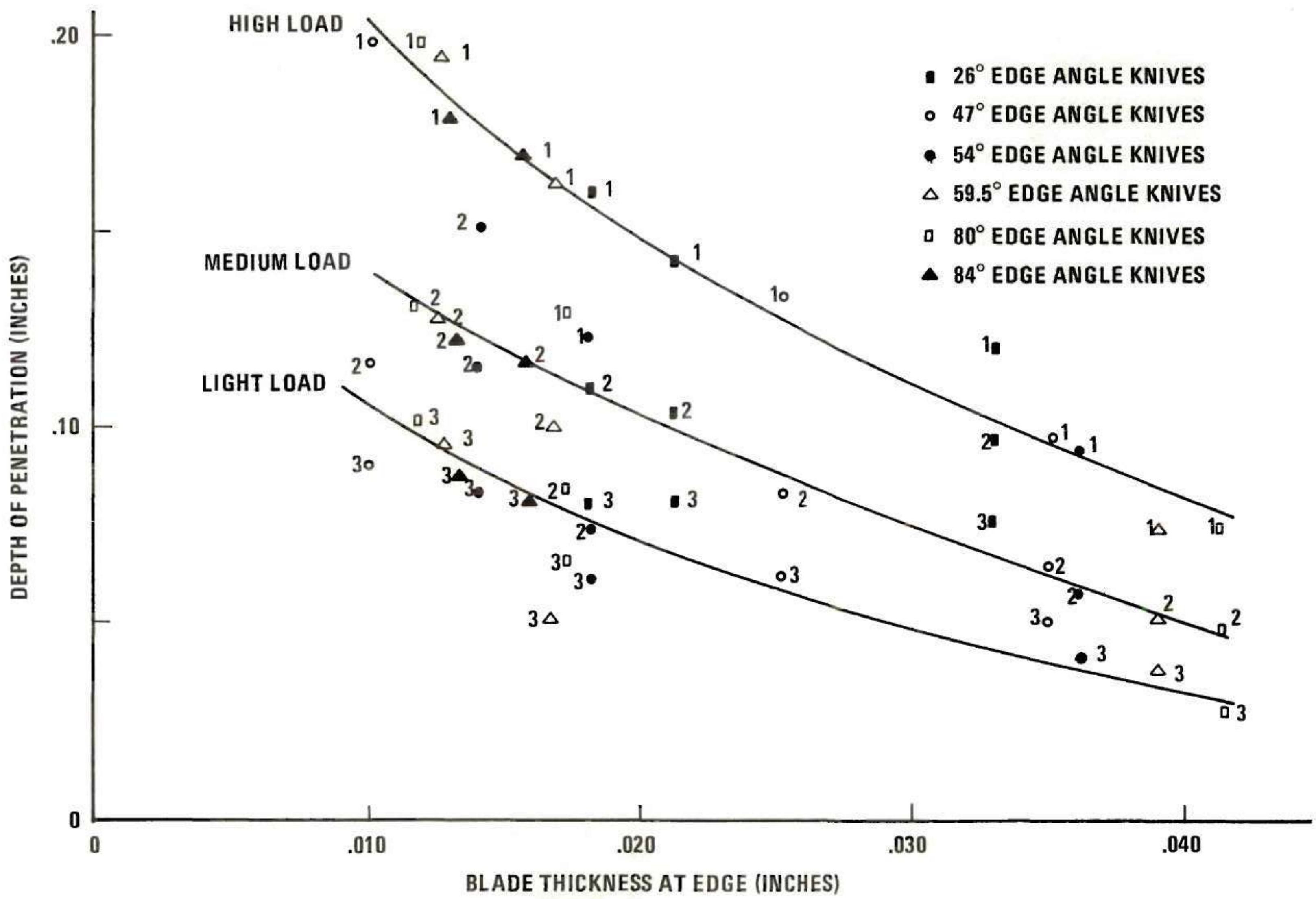


Figure 19. Dependence of Depth of Penetration on Blade Thickness at the Edge.

bending and fracture as the thickness diminishes. The cutting penetrability test did not measure the blade's resistance to failure, only its ability to penetrate the medium. Therefore, a measure of the material's strength had to be included in order to obtain a realistic evaluation of the optimum knife blade thickness at the cutting edge.

Results of Material Strength Tests

The bending tests performed on the Tinius-Olsen Stiffness Tester were used to establish the lower end point of the blade thickness range. From the standpoint of ease of penetration, it is desirable to have a very thin knife edge, but the blade must have sufficient strength to endure the rough usage it encounters. The strength property required here is actually material toughness, the ability of the material to resist deformation or fracture. The property of material toughness is important to the blade's ability to resist breakage, but a hard material is needed in order to retain the sharpness of the blade for long periods of usage. The problem, as previously mentioned, is that hardness and toughness are inversely related.

Since specimens were prepared at different thicknesses and hardnesses, the idea of hardness and material toughness should be related. The knife material considered in this study was 440C stainless steel. The microstructure of the steel may consist of any combination of ferrite, austenite, martensite, and carbides depending on the heat treatment. The material the bending specimens and the knife specimens were made from was quenched and tempered; therefore, the microstructure consisted of martensite, or tempered martensite (if the material was tempered from the quenched hardness), retained austenite, and carbides. High hardnesses (Rockwell "C" 60) are obtained in 440C when martensite is present and the amount of retained austenite is low (440C stainless steel of Rockwell "C" 60 hardness normally contains about 30 per cent by volume retained austenite). When the material is in the hardened state, the material is very resistant to deformation, the point at which fracture occurs is almost coincident with the point of plastic deformation. As the hardness is reduced, the point of fracture occurs further and further from the point of plastic deformation. This means that the material can absorb more strain (plastic deformation) before fracture occurs and therefore the material is considered tougher. The ideal is to obtain a hard material that is also tough, but since the trends for hardness and toughness are inversely related, a compromise must be made.

Method of Presenting Results

A preliminary study of fractures sustained by knife blades that had very thin leading edges showed that bending was the major cause of failure. The stress distribution in a material experiencing a bending mode is quite different from the stress distribution of the same material in tensile loading. Under a bending load one surface is in tension and the opposite surface is in compression; in tensile loading both surfaces are in tension.

The Tinius-Olsen Stiffness Tester permitted a reproducible means of bending the specimens and of obtaining stress versus strain curves for each test. The apparatus recorded stress in terms of per cent of the maximum load (in inch-pounds) supported by the specimen and strain

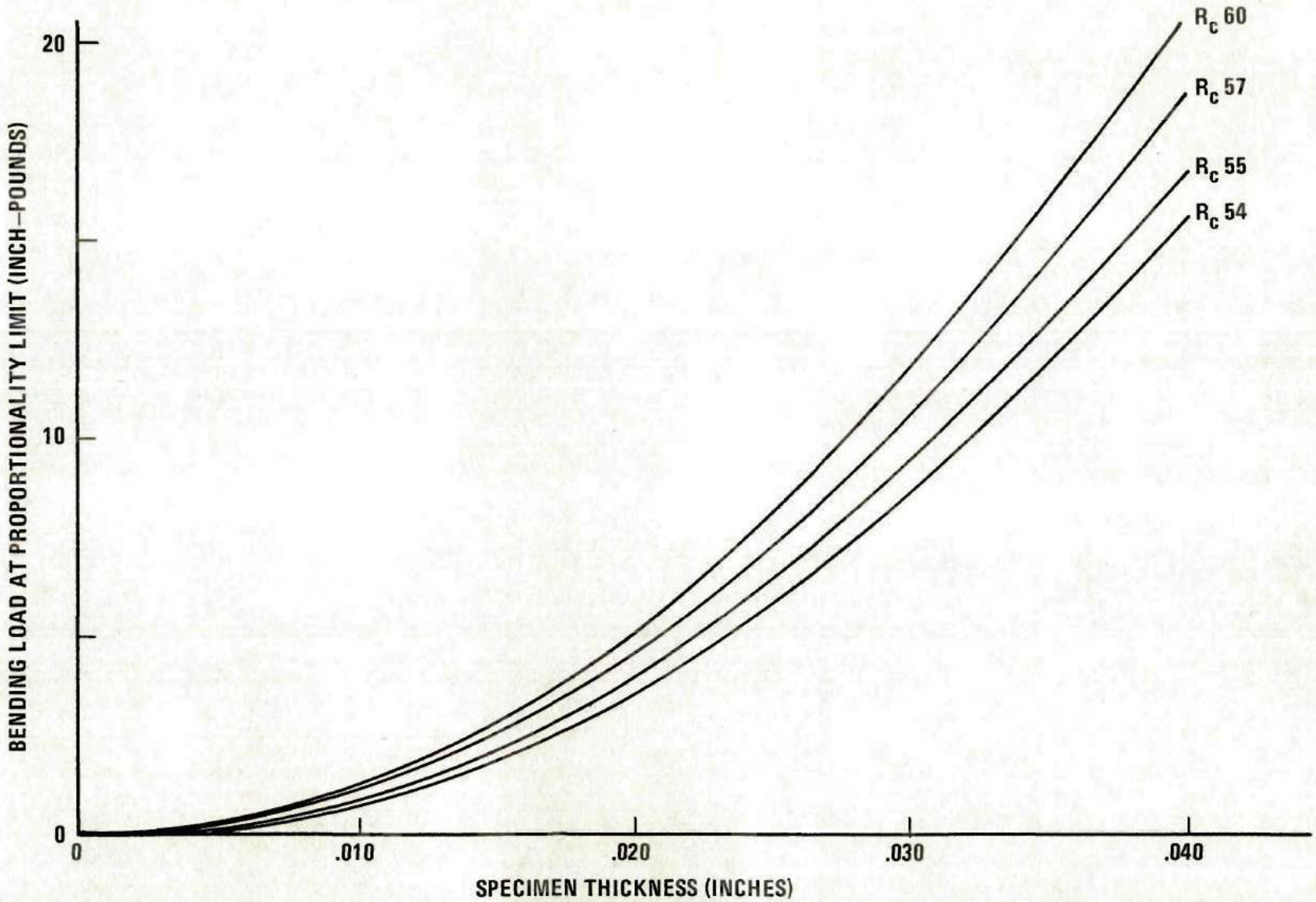


Figure 20. Dependence of Proportionality Limit on Material Thickness and Hardness.

in terms of degrees deflection of the specimen from the zero load condition to the load level at which the reading was taken.

The stress-strain curves presented three pieces of information about the materials mechanical properties: 1) the modulus of elasticity, 2) the proportional limit or yield point, and 3) the fracture point (for the .020 and .010 inch specimens only). Of the three material characteristics, the proportional limit was judged to be the most germane (the proportional limit is the point at which the stress becomes non-linear with the strain, the material begins to deform plasticly instead of elasticly). If the cutting edge is bent to one side (away from the centerline of the blade's cross section), the apex of the cutting edge angle is directed away from the direction of the cut and the knife is effectively dull. If the edge is bent further, then the edge is likely to fracture. This directs more emphasis on the blade's rigidity (ability to resist bending) than on the point at which it fractures. Therefore, the dependence of the proportional limit on the specimen thickness and hardness was extracted from the stress-strain curves. This dependence is plotted in Figure 20.

<u>Meaning of Bending Results.</u> The trend, verified by Figure 20, shows a decrease in material strength with decreasing thickness. It can also be seen that the material hardness also affects the curve. The hardness effect is stronger in the thicker specimens than in the thinner specimens.

In terms of determining the optimum blade thickness at the edge, this result cannot stand alone. The curve does establish a lower limit for material strength. At specimen thicknesses less than .008 inch the load necessary to bend the specimen is virtually zero, this strength level definitely could not be tolerated in a knife edge. Determinations of the optimum value for the blade thickness at the cutting edge depends on combining the results of the penetrability tests with the results of the material strength tests.

Evaluation of Optimum Blade Thickness at the Edge

The penetrability tests established the desirability of employing thin leading edges for increased penetration of a medium. The material strength tests showed that the thin blades are much weaker than the thicker blades. These two properties, ease of penetration and material strength, are the important factors affecting the optimum thickness of the knife blade at the cutting edge.

Method of Combining Penetrability and Material Strength Results

Since each set of results has a trend that is inversely related to the other and is, when taken alone, insufficiently conclusive (discussed in the two previous sections), some means of combining them had to be found. The problem is that the units of each set of results are dissimilar. Penetrability was expressed as depth of penetration in inches versus thickness and material strength was expressed as load in inch-pounds required to cause plastic yielding versus thickness. There appears to be no direct relationship between material strength and depth of penetration, yet, as the discussion so far has stated, the blade can only be made so thin and then the edge becomes extremely susceptible to breakage and bending, neither of which can be tolerated.

It was decided that the best means of negotiating this problem would be to normalize each set of data to its average value and then to assign a weighting factor to each set of normalized data. The data would then be plotted on the same scale and the curves added, to obtain a composite curve that would reflect the two-fold dependence of the edge thickness. Figure 21 is an illustration of this type of plot.

Resultant Optimum Blade Thickness at the Edge

The curve in Figure 21 is based on assigning equal weight to the penetrability and material hardness trends. A 50-50 weighting of the averages appeared to be realistic since neither the penetration ability nor the material's strength could be considered more important than the other. A second advantage of equally weighting the trend was that it provided a midpoint, if it were desired to place a different weight on each factor then one can easily predict which direction the optimum will move and about how far it will shift.

Figure 21 was plotted to show the influence of both load level on the penetrability and hardness on the material strength. The resulting composite curves also reflect these effects. For knife blades of about Rockwell "C" 54, the optimum thickness varies from .015 to .0175 inch for low load levels up to .021 to .0225 inch for high load levels. For blades of about Rockwell "C" 60 the optimum thickness varies from .008 to .0096 inch for low load levels up to .017 to .019 inch for high load levels. If the penetrability is judged to be more important than the material strength, the curve can be expected to shift toward a thinner blade at the edge. If the opposite is desired, a stronger blade, the desirable blade thickness would be greater. The

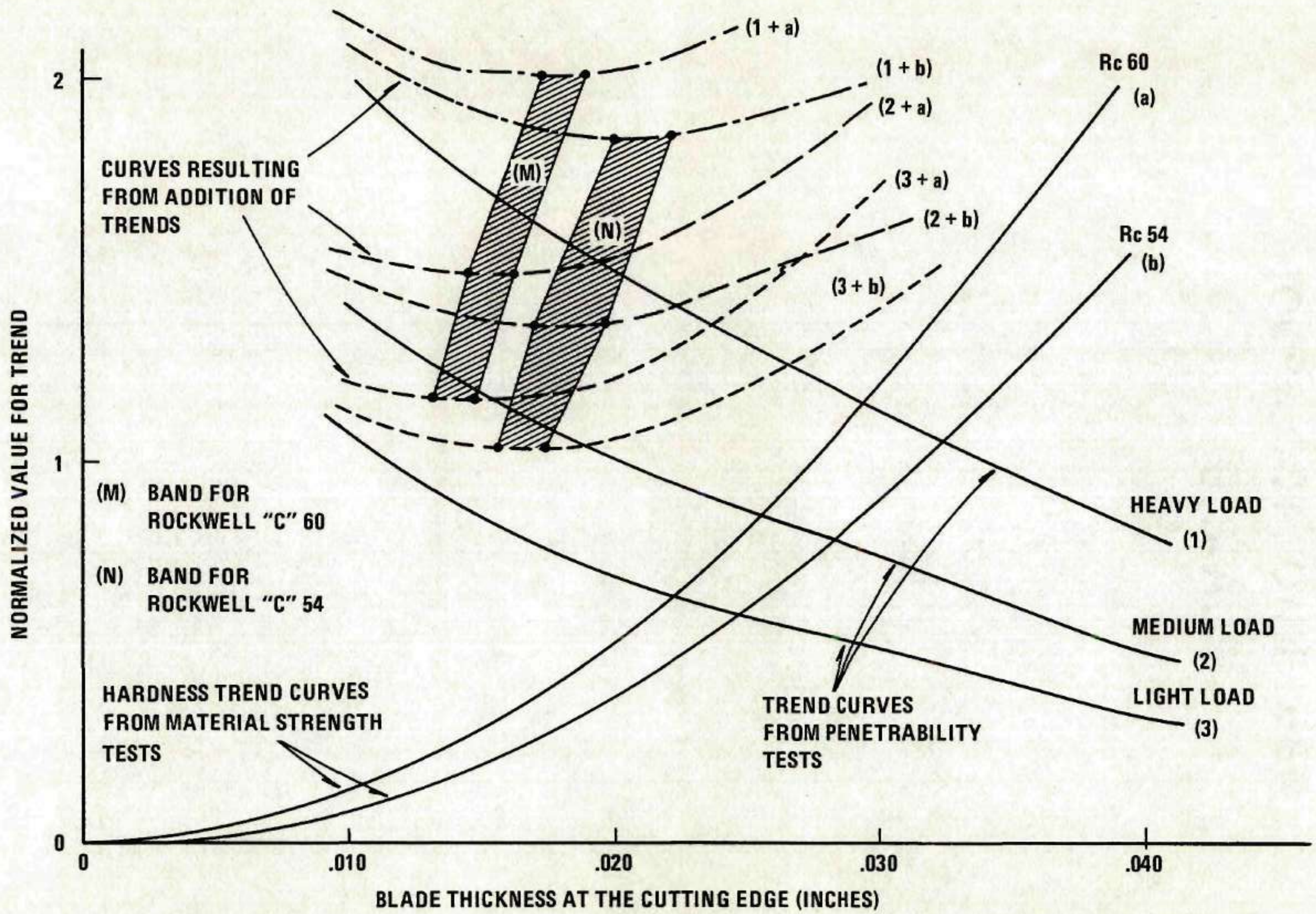


Figure 21. Determination of Optimum Blade Thickness at the Edge.

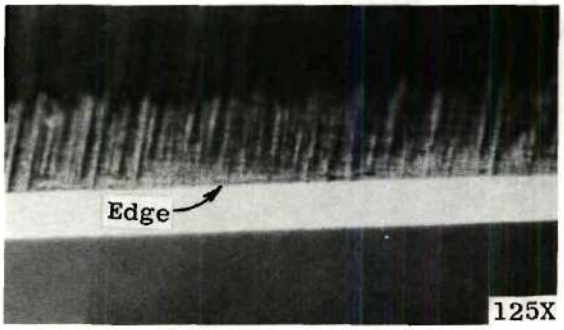
curve also shows that increased penetrability can be obtained without a loss in material strength if a harder, thinner leading edge is employed.

Effect of Edge Finish on Sharpness Longevity

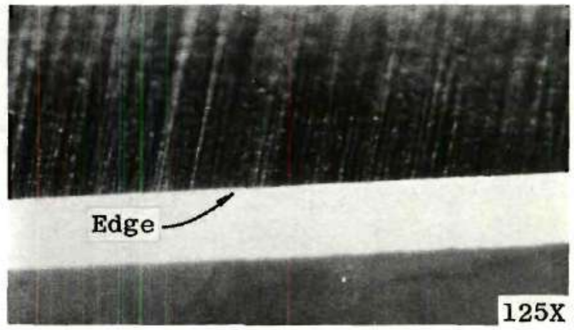
The effect of the quality of the finish given the leading edge was derived from the macroscopic examination of several hundred knives in various stages of dullness. It was consistently observed that the edges with the best finishes lasted longer and were subject to fewer failures. Figures 22 and 23 are a catalogue of macrographs illustrating various undesirable leading edge conditions commonly encountered in the cutlery studied.

The quality of the edge finish refers to the smoothness, regularity, and uniformity of the grinding striations caused by the various stages of knife grinding. Although the ultimate in an edge finish is a polished surface, this is neither practical nor particularly desirable for cutlery of this nature. The expense involved in obtaining a polished finish places it out of the realm of feasibility. The second factor to be considered if the knife's performance during cutting.

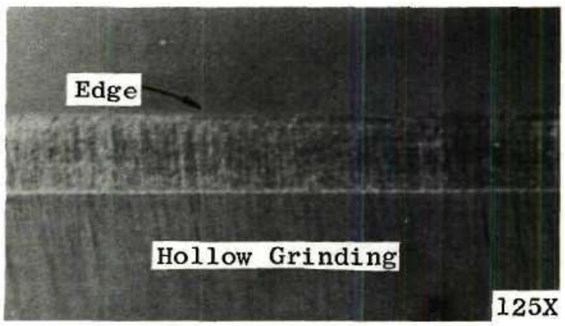
If the cutting edge is a polished surface, the total cutting power is derived from the cutting edge's ability to sever the fibers of the meat. If small "nicks" (grinding striations) are present, the cutting power is enhanced by a saw type action. If these "nicks" are very large, of course, the edge tears its way through the meat, but if the "nicks" are quite small, the tearing is on a very small scale and the cutting power is, thereby, increased. The advantages of this effect



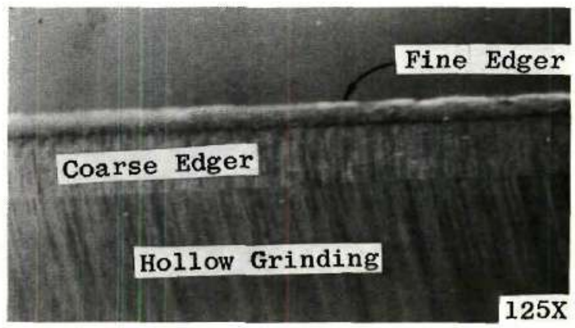
Coarse Grinding Striations



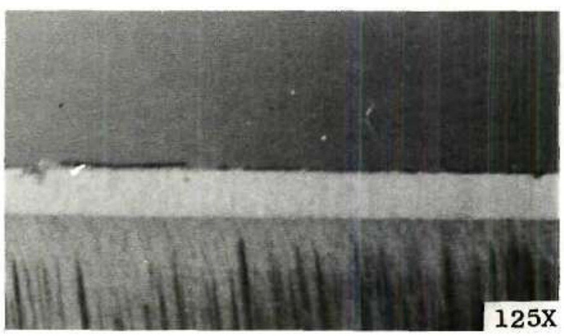
Fine Grinding Striations



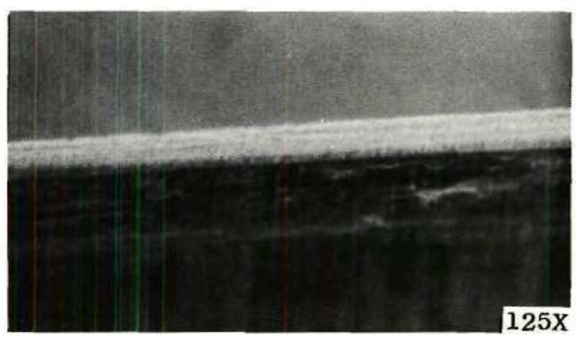
Properly Ground Edge



Edgers Not Set to the Same Angle

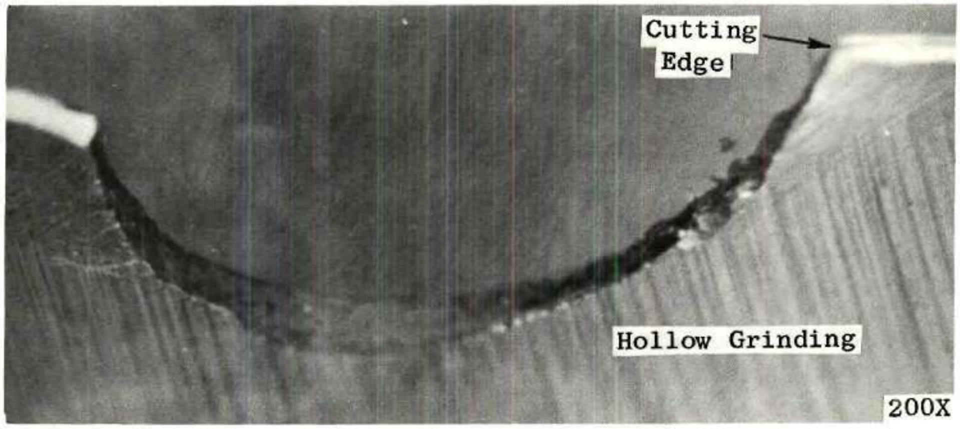


Wire Edge

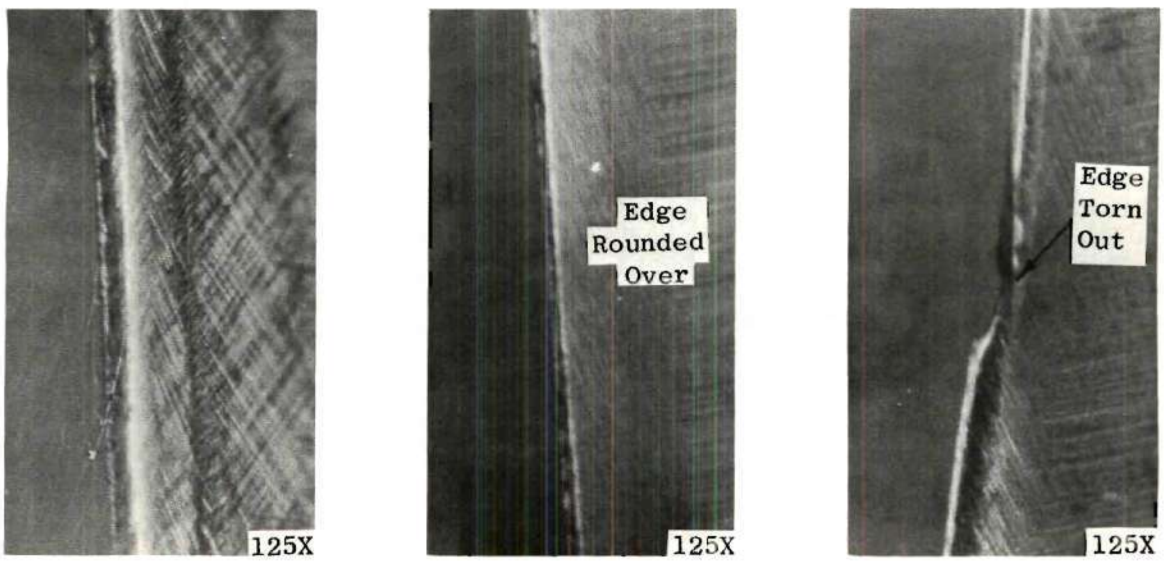


Experimentally Dulled Edge

Figure 22. Macrographs of Typical Knife Edge Conditions.



Gap in Edge Due to Too Thin a Blade at the Edge



Edges Dulled in Meat Market Usage

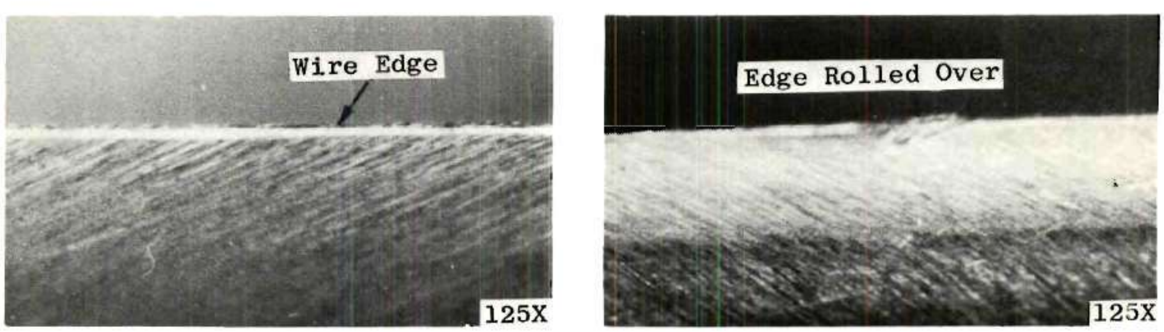


Figure 23. Macrographs of Typical Knife Edge Conditions

must be balanced against the expense of finishing the edge to the desired smoothness (a factor not investigated in this study).

It was found that edges that were not finished on the 400 grit abrasive edging wheels were prone to earlier degradation than the edges finished on the 400 grit wheels. The grinding striations of the coarse edging wheel caused the cutting edge to be jagged and, therefore, more susceptible to rapid dulling from tearing of the edge.

A smooth finish has two other advantages. First, a smooth edge will have less friction with the cutting media. This means that more of the force applied to the knife edge will go into cutting and less into moving the blade against the frictional forces present during cutting. Second, a smooth finish is more resistant to corrosion. The valleys between the striations are difficult to clean of meat juices and particles and are thus excellent sites for corrosion to begin. Very small amounts of corrosion at the cutting edge could cause severe deterioration in a relatively short period of time. As the finish given the edge becomes smoother, corrosion in the striation crevices is less likely because the crevices become shallower and easier to clean.

The observations that were made showed the 400 grit finish to be adequate. If the economics permit further finishing of the knife edge, then a step up in the edge finish quality should be made.

Several other factors affecting the edge finish were previously discussed in the sections preceding this. The wire edge problem was explored in the section covering the dulling curve results for small edge angle knifes. Asymmetric grinding of the hollow grinding and the edge angle were discussed in the experimental procedure for forming the leading edge of the knives.

CHAPTER V

CONCLUSIONS

The results of this investigation may be summarized in the following conclusions:

1. The sharpness longevity of the cutting edge is a function of the cutting edge angle and the hardness of the blade material (not dependent on the blade thickness at the edge).

2. Increasing the hardness of the blade material from Rockwell "C" 55 to Rockwell "C" 60 yields a dramatic increase in the sharpness longevity of the cutting edge.

3. The optimum cutting edge angle for a knife blade made of 440C stainless steel is between 44 and 48 degrees.

4. The ability of the leading edge of the knife blade to penetrate a paraffin medium is solely a function of the blade thickness at the edge, i.e., it is not dependent on the angle of the cutting edge.

5. For knife blades of about Rockwell "C" 54, the optimum thickness varies from .015 to .0175 inch for low load levels up to .021 to .0225 inch for high load levels. For blades of about Rockwell "C" 60, the optimum thickness varies from .008 to .0096 inch for low load levels up to .017 to .019 inch for high load levels.

6. The cutting edge should be finished to whatever smoothness the economic situation will allow.

7. The optical evaluation of the knife edge sharpness is sufficiently reliable and fast to be used as an on-line quality control technique on the finished knife edge.

APPENDIX

THE ROLE OF HOLLOW GRINDING THE LEADING EDGE OF THE KNIFE

Hollow grinding is a technique of knife finishing that has become quite popular in recent years. Hollow grinding is a concave grinding of the knife blade at the leading edge. The result is a thinner leading edge. A thin leading edge has two desirable effects. First, the wedging effect of the blade passing through the medium being cut is greatly reduced. Second, the friction between the knife and the cut material is reduced as there is less blade thickness at the point of cutting, hence, less area for friction to be exerted. The total effect is for the knife edge to more easily penetrate the material, and less force is required.

Hollow grinding, however, does have two drawbacks. First, the thinner edge is not as strong. The reduced thickness makes the edge more susceptible to breakage when a bending force is applied to the edge. The second problem arises from the grinding of the concave surface. If special care is not exercised during the grinding, then the material can be overheated, and tempering can occur. As the edge is ground thinner, there is less material present to dissipate the grinding heat generated. The result is a soft material for the cutting edge; this means a short sharpness lifetime for the cutting edge.

Assuming that, one, the knife edge is properly cooled during the grinding in order to prevent softening and, two, that the knife is hollow ground to a thickness commensurate with its usage, i.e., a thick edge for abusive use and a proportionally thinner edge for lighter usage, then the hollow grinding has a completely favorable effect on the knife's performance.

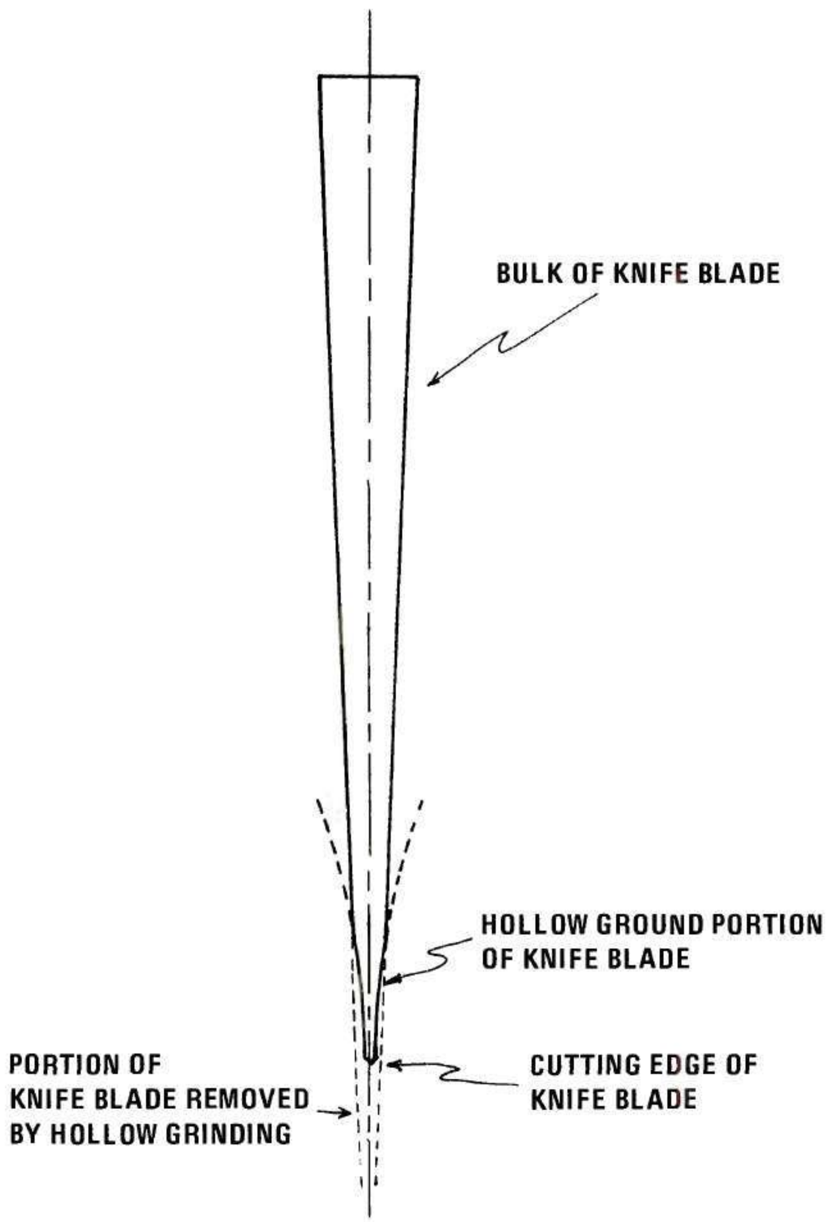


Figure 24. Sketch of Hollow Ground Knife

$$\theta = 360 - 180 - 2\phi$$
$$= 180 - 2\phi$$
$$\theta = 90 - \psi$$
$$\psi = \cos^{-1}\left(\frac{R - X/2}{R}\right)$$
$$= \cos^{-1}\left(1 - \frac{X}{2R}\right)$$
$$\theta = 180 - 2(90 - \psi$$
$$\theta = 2\psi$$

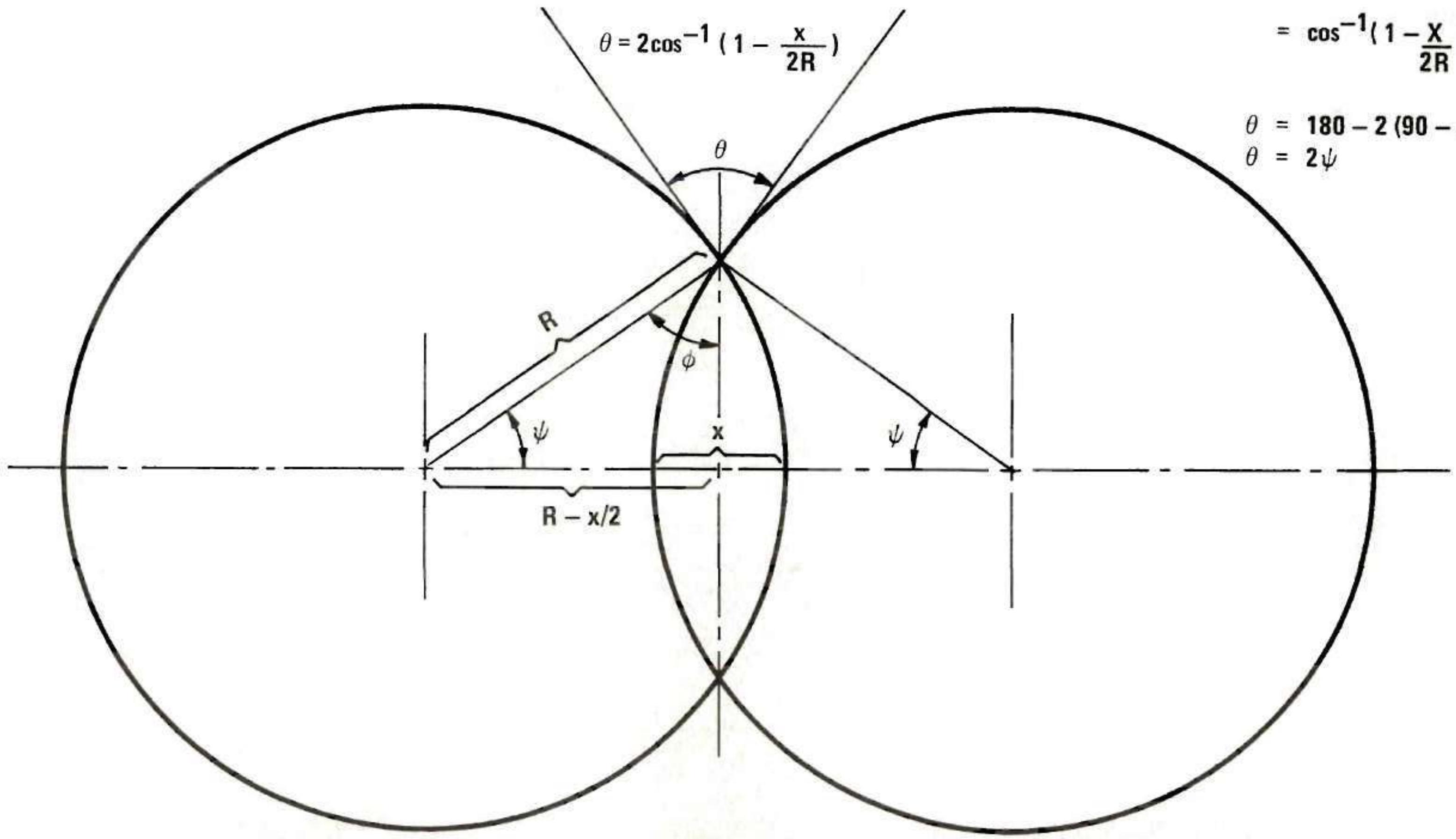


Figure 25. Schematic of Edge Grinding Wheel's Configuration.

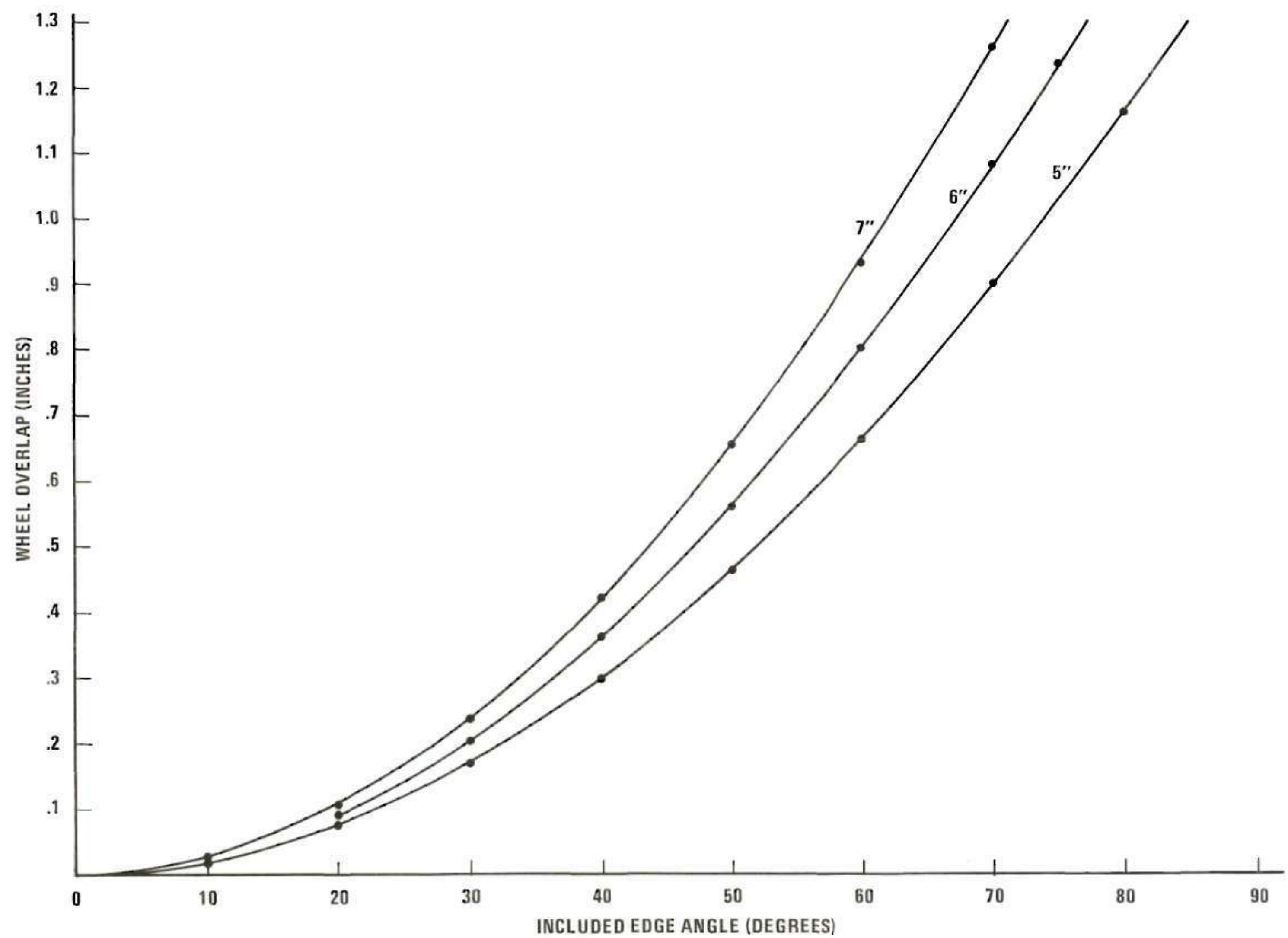


Figure 26. Relation of Edge Angle Ground to Amount of Wheel Overlap.

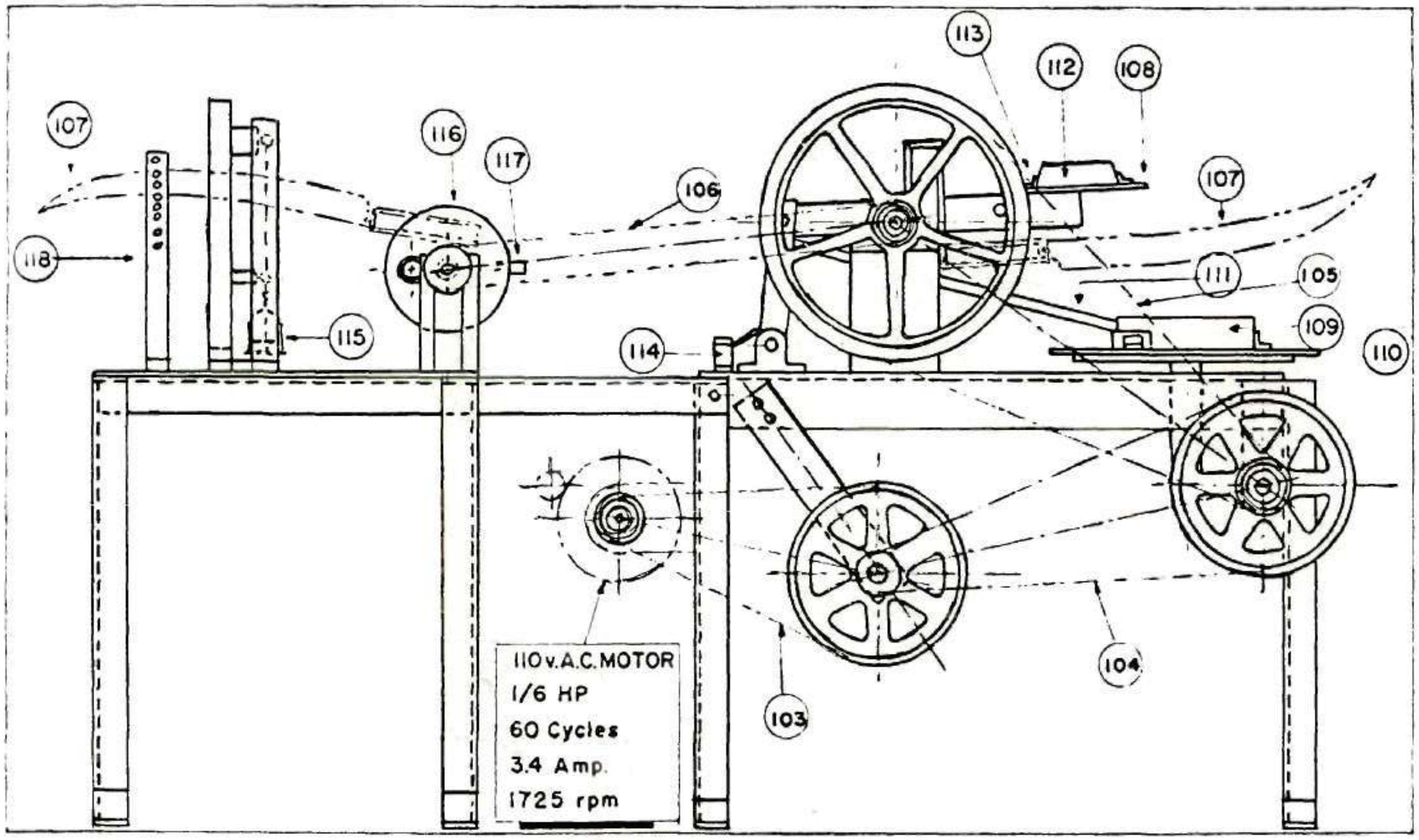


Figure 27. Sketch of N. A. Milone's Scoring and Sharpness Testing Machine.

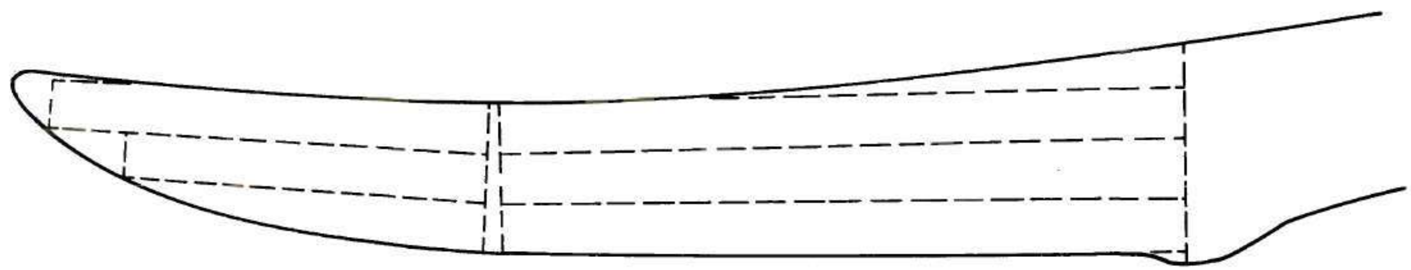


Figure 28. Sectioning of Hardened Knife Blanks for Bending Test Specimens.

THE EFFECT OF STEELING ON THE SHARPNESS LIFETIME OF THE CUTTING EDGE

Steeling is a technique for "restoring" the sharpness of a cutting edge after a period of usage. The steeling process is accomplished by stroking the knife edge against a hard steel rod, or more recently a ceramic rod. The actual function of steeling is to straighten the cutting edge so that it is directed along the centerline of the knife cross section (the direction of the cutting force) and not to one side or the other.

Steeling is of great value, especially, with knives having a very small edge angle or having a very low blade thickness at the edge. This indicates that cutting edges that are quite susceptible to bending or distortion, such as the ones mentioned previously, can be aided by steeling, but only if properly performed.

Proper steeling should accomplish the goal of straightening the cutting edge and not be carried further. The knife should be held at the proper angle, which is the same angle at which the edge angle was originally ground, and only moderate pressure should be applied between the steel and the knife edge. Of these two requirements, maintaining the knife at the correct angle is the most critical. If the steeling angle is greater than the edge angle, then the pressure is on the tip of the edge angle. This will cause over correction with each steeling stroke and speedy fatigue of the cutting edge, leaving a dull surface in the place of the bent, but sharp edge that was fatigued to fracture.

The pressure exerted on the knife in this case would affect the speed with which the edge is fatigued to fracture. The greater the pressure the sooner the edge will fracture.

If the steeling angle is smaller than the original edge angle, then the pressure will be against the rear portion of the edge taper and the cutting edge will not be touched by the steel (no straightening can be affected). In this case, the effect of pressure is minimal since the pressure is not directed against the cutting edge.

The last case is maintenance of the correct steeling angle. Meeting this condition will insure proper realignment of the cutting edge and prolonged usefulness of the knife.

The steels made of hardened steel do not remove any metal from the edge, except from fatigue breakage. Recently, however, ceramic steels have become popular and these steels remove small amounts of material. If the proper steeling angle is maintained, then this is a possible aid, but if the steeling angle is in error, then the knife can be dulled or a wire edge produced, depending on the steeling angle used.

In view of the results obtained in this study, the value of steeling a knife ground to the suggested optimum leading edge configuration would be of little or no value to the sharpness longevity of the leading edge. Since the dulling of the suggested edges is primarily a wear dependent phenomenon, an operation similar to steeling could be of value. By drawing the cutting edge angle against a very fine abrasive, small amounts of material could be removed from the dulled cutting edge, thereby, restoring a portion of the blade's original sharpness. It is extremely important for the correct angle between the blade and the abrasive surface to be maintained. A small jig for this operation could be prepared for use in markets, to replace the conventional butcher's steel. In either case, this study indicates that steeling as it is now known should be eliminated from meat processing sites.

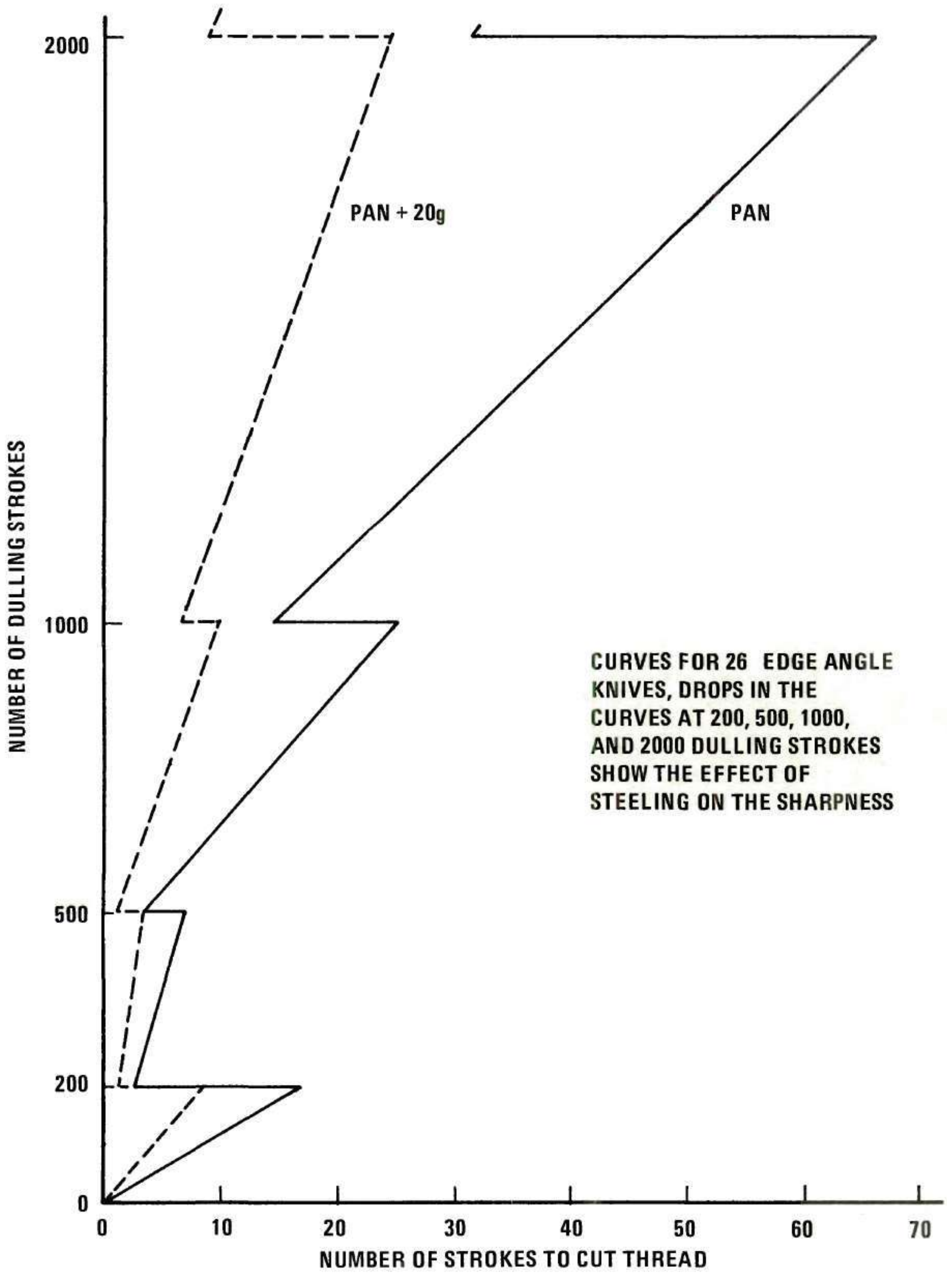


Figure 29. Effect of Steeling on Small Edge Angle Knives.

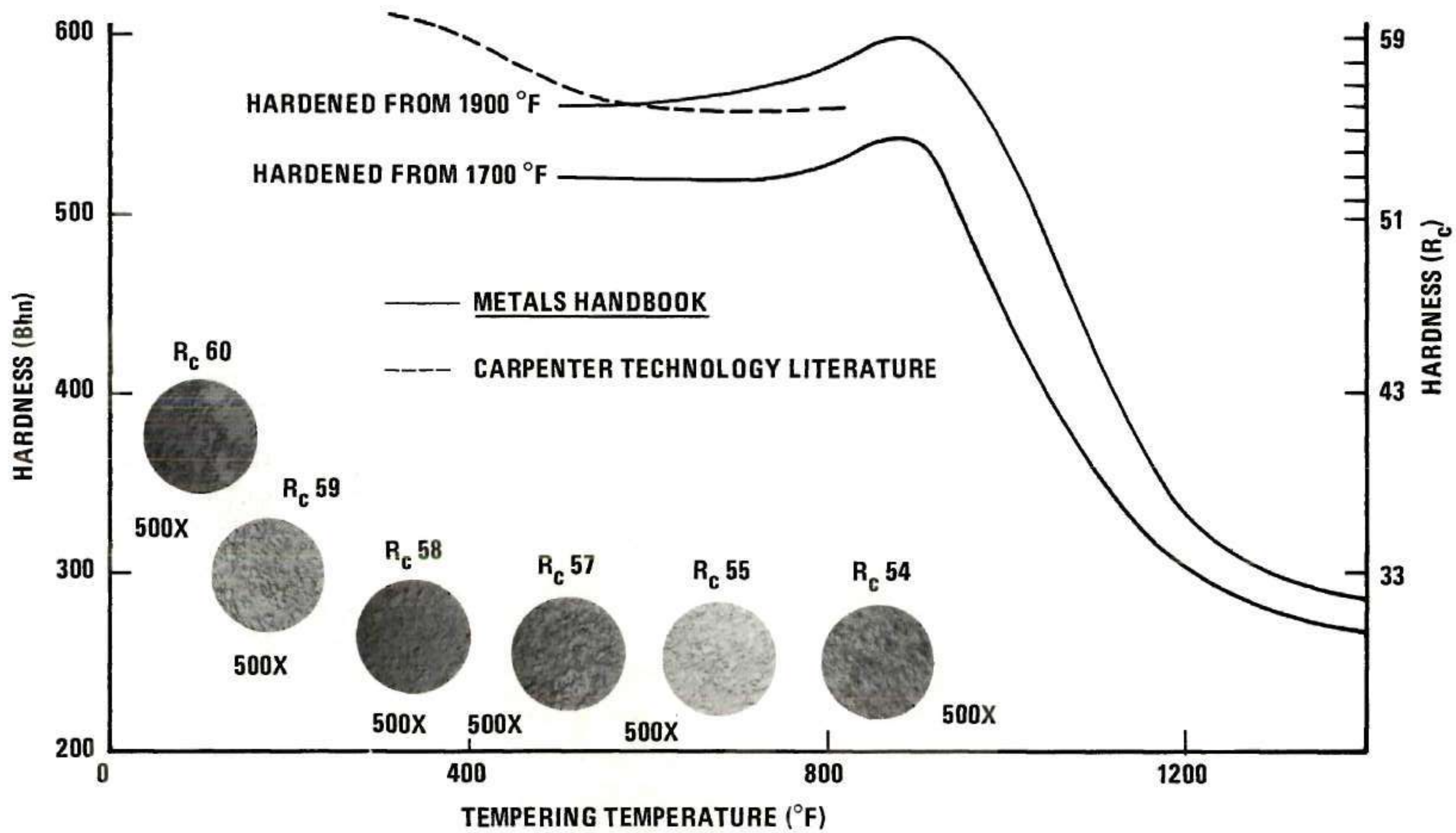


Figure 30. Microstructures of 440C Stainless Steel at Various Hardnesses.

BUTCHER PREFERENCE SURVEYS AND OTHER GENERAL FINDINGS

In the early stages of this research a great deal of work was done in local Atlanta meat markets. It was the aim of this survey to learn first hand what types of usage professional cutlery received and also to learn what characteristics of the knife blade the butcher's were most concerned over. Knife blades were ground to various leading edge configurations and degrees of edge finish. The results obtained were, of course, quite qualitative, but they did reveal a number of interesting facts.

The majority of meat market knife usage falls into three broad areas: 1) table work, 2) rough shaping, and 3) boning. Table work includes the final finishing of the cut of meat, i.e., final shaping and removal of excess fat and poor quality areas. In rough shaping the bulk pieces of meat are cut into the sub-units from which the finished cuts are taken. The boning operation removes the bulk chunks of meat from the main support bones.

The roughest knife usage occurs during boning. The general preference expressed by some thirty butchers was for a "stouter" knife for this operation. The knives prepared for this study that met these desires best were the blades with larger edge angles and moderately thin edges (at this point the common edge angle was 26 degrees; the thickness of the edge was an unknown). The smaller edge angles were said to dull too fast. The quality of the edge finish did not make much difference in this operation.

The coarse shaping operation mainly involved larger knives (about 12 inches long). Because of this, the information obtained was incomplete, and not conclusive enough to draw an opinion from.

The table work can be either light duty or heavy duty depending on the butcher's technique. This operation pointed out some very interesting facts. The type of meat being cut strongly affected the preferences. For cutting veal a very fine edge with a rough finish was desired. This configuration was also preferred for cutting liver and other similar meats. Cutting of beef and similar heavy meats required a smooth edge finish. The thinner blades were preferred. The small edge angles cut better, but the longer sharpness lifetime of the larger edge angles was judged to be of more value.

A second series of tests were run to set limits on the useful sharpness lifetime of the cutting edge. The sharpness limit was set at the point when the butcher would have considered the knife "dull" enough to warrant steeling (see earlier discussion). The results of these tests were utilized to set the sharpness limits for the experiments of this study.

Several other characteristics came to light that were entirely a function of the individual butcher's preference. These included the overall shape of the knife blade, whether it was straight or curved; the knife handles shape and material of construction, and the stiffness of the overall blade, whether it was pliable or stiff. These factors, of course, cannot be optimized as they will vary so greatly from butcher to butcher.

Yet another factor was found to be important and that was the composition of the cutting board material; as this subject has been quite thoroughly explored by N. A. Milone (see references in bibliography), it will not be discussed here.

Verification of the experimental reproducibility of the results was needed for establishing confidence in the work. This verification took two forms: internal reproducibility and external verification. The internal reproducibility was established using knives having edge angles of about 15 degrees and about 26 degrees. The smaller edge angles were used because of the speed of dulling, thereby giving results much faster. Approximately fifty knives having these edge angles were dulled on the multi-purpose knife tester and their dulling curves compared. Knives having the same edge angle and comparable edge finishes had similar dulling curves. Optical observation of the cutting edge at the various stages of dulling enables identification of edge conditions that might contribute to changes in the average dulling rate for a particular edge angle knife. These studies along with those of N. A. Milone assured sufficient confidence to be placed in the experimental techniques used in this study.

The external verification came from the butcher preference surveys previously discussed. Knives sharpened at the optimum leading edge configuration were prepared and tested in a number of meat markets. The concensus of these tests was that the knives were remarkably better than the knives which they had been using. The edges stayed sharper longer than any they had seen before and the overall performance was praised by all the butchers.

These tests also verified the logic used in setting equal weights to the material strength and the cutting penetrability. When the thickness at the edge of the blade was increased to the value found from Figure 21, the amount of edge breakage and gapping of the edge was virtually eliminated. Prior to this result, an excessive number of knife edges were destroyed due to damage from gapping and breakage. After adopting these values as part of the production practice, these problems disappeared.

Table 1. Dull Out Points of Knives Cited in Discussion of Results

Knife Number	Edge Angle	Pan	Pan + 10g	Pan + 20g	Pan + 30g	Pan + 50g
1	11.5°	100	600	600	600	600
2	11.5°	-	-	-	-	-
3	11.5°	-	-	-	-	-
Average		100	600	600	600	600
4	26°	300	1000	1500	6000	6000
5	26°	200	500	900	2000	2000
6	26°	150	250	400	1000	1000
Average		216	583	933	3000	3000
7	47°	-	-	-	-	-
8	47°	10	500	1000	1500	2000
9	47°	10	1000	10,000	10,000	10,000
Average		10	750	5500	5750	6000
10	54°	1000	1500	2000	2000	2000
11	54°	10	600	800	1000	1000
12	54°	-	-	-	-	-
Average		505	1050	1400	1500	1500

Table 2. Depth of Penetration of Knives into the Paraffin Blocks

Knife #		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
Load on Knife (oz) / Knife Penetration (in)	48.00	.148	.120	.101	.087	.085	.078	.089	.062	.051	.085	.056	.045	.051	.097	.042	.104	.068	.032	.076	.084	
	53.25	.136	.135	.112	.101	.095	.091	.106	.077	.059	.100	.067	.053	.084	.114	.045	.117	.075	.041	.092	.096	
	58.66	.141	.144	.122	.113	.105	.099	.116	.084	.067	.117	.076	.058	.101	.130	.052	.136	.087	.048	.100	.110	
	64.00	split	.157	.133	.127	.121	.103	.141	.105	.080	.130	.088	.065	.114	.138	.058	.153	.096	.050	.114	.125	
	80.00		split	.156	.149	.136	.131	.192	.125	.098	.141	.111	.082	.150	.166	.071	.179	.117	.063	.150	.151	
	85.33			.164	.160	.146	.130	split	.134	.099	.154	.126	.095	.165	.194	.077	.202	.128	.075	.169	.169	
	90.66								.138	.103	.191	.135	.103	split	.187	.070	split	.143	.081	.193	.184	
	96.00															.075			.087			
Knife Charac-teristics	Thickness	.012"	.013"	.013"	.018"	.021"	.033"	.010"	.025"	.035"	.013"	.018"	.036"	.012"	.0165"	.039"	.0115"	.017"	.042"	.0125"	.015"	.044"
	Edge Angle	11.5^{o}	11.5^{o}	11.5^{o}	26^{o}	26^{o}	26^{o}	47^{o}	47^{o}	47^{o}	54^{o}	54^{o}	54^{o}	59.5^{o}	59.5^{o}	59.5^{o}	80^{o}	80^{o}	80^{o}	84^{o}	84^{o}	84^{o}

Table 3. Characteristics of Bending Test Specimens

Specimen Number	Average Thickness (in)	Average Hardness (DPH)	Proportionality Limit (in-lb moment)
1	.0800	743	-
2	.0805	631	-
3	.0800	634	-
4	.0380	711	19.20
5	.0385	702	18.80
6	.0395	799	14.50
7	.0395	681	-
8	.0400	669	-
9	.0380	687	19.30
10	.0385	699	18.20
11	.0396	619	19.40
12	.0383	636	19.40
13	.0390	609	-
14	.0392	604	16.50
15	.0375	622	16.50
16	.0410	605	-
17	.0218	755	4.25
18	.0162	653	4.38
19	.0217	711	4.88
20	.0210	705	3.78
21	.0196	744	4.30
22	.0204	694	4.30
23	.0227	662	5.73
24	.0230	656	5.56
25	.0181	696	3.70
26	.0202	690	4.88
27	.0198	645	4.15
28	.0204	626	4.35
29	.0206	616	4.25
30	.0193	618	4.18
31	.0110	758	1.41
32	.0089	744	.76
33	.0126	696	1.85
34	.0125	723	1.72
35	.0101	705	1.04
36	.0102	717	1.14
37	.0162	642	2.90
38	.0142	672	2.51
39	.0147	623	2.71
40	.0151	638	2.56
41	.0135	645	2.10
42	.0129	618	1.89
43	.0165	664	3.29
44	.0795	624	-
45	.0797	626	-
46	.0792	589	-

Table 4. Raw Data for Bending Curves of .080 inch and .040 inch Specimens

.040" thick 20 in-lb moment

Plot Symbol	▲	△	○	▫	●	▫	○	△	●	▫	△	●	○	▫	□	●	○	●	▫	●	▫	○	○	△	●	▫
Specimen #	4	5		6		7		8		9		10		11		12		13		14			15		16	
% Moment																										
5																										
10	1.5	1.3	1.3	1.3	1.1	1.1	1.2	1.4	1.2	1.4	1.5	1.3	1.3	1.0	1.1	1.2	1.2	1.3	1.2	1.5	1.3	.9	1.6	1.3	.9	1.1
15																										
20	3.6	3.0	2.6	2.7	2.5	2.3	2.7	2.8	2.5	2.9	2.8	2.6	2.7	2.4	2.2	2.6	2.5	2.6	2.5	2.7	2.7	2.0	3.3	2.8	2.2	2.3
25																										
30	5.0	4.5	4.0	4.00	3.8	3.5	3.8	4.1	3.8	4.3	4.1	4.2	4.1	3.6	3.6	3.8	3.7	3.9	3.7	3.9	4.1	3.1	4.6	3.9	3.2	3.4
35																										
40	6.0	6.1	5.3	5.1	4.8	4.7	5.0	5.1	4.9	5.7	5.5	5.3	5.5	4.8	4.9	5.2	4.6	5.1	4.9	4.8	5.2	4.2	5.8	4.9	4.4	4.6
45																										
50	7.0	7.3	6.5	6.2	5.9	5.6	6.0	6.2	5.8	7.1	6.7	6.4	6.6	5.8	6.2	6.6	5.6	6.1	5.9	5.8	6.2	5.5	7.2	5.8	5.2	5.4
55	8.0																									
60	8.5	8.5	7.6	7.3	6.9	6.5	7.0	7.1	6.7	8.2	7.8	7.3	7.7	6.7	7.4	7.7	6.6	7.0	7.0	6.9	7.2	6.3	8.3	6.9	6.1	6.2
65	9.0																									
70	9.5	9.5	9.0	8.5	8.0	7.5	8.0	8.0	7.5	9.3	8.8	8.3	8.7	7.6	8.3	8.7	7.5	8.1	7.8	8.0	8.4	7.3	9.6	7.8	6.9	7.2
75	10.3				8.5	8.0																				
80	10.7	10.7	10.4			8.5	9.1	9.0	8.5	10.6	10.0	9.5	10.0	8.7	9.4	9.6	8.5	9.2	9.0	9.2	9.6	8.4	11.2	8.8	7.8	8.0
85	11.3	11.5	10.8			9.1																				
90	12.0	12.1	11.5			9.5	10.2	10.0	9.3	12.1	11.2	10.7	11.3	9.7	10.5	11.1	9.6	10.2	10.1	10.4	11.2	9.6	13.0	9.9	8.8	9.1
95		12.8	12.4			10.0		10.5	10.1														14.0	10.4		
100	13.0	13.8	13.3			10.5	11.5	11.1	10.6	13.6	12.4	12.3	12.8	10.5	11.6	12.5	10.6	11.6	11.3	12.1	13.1	10.7		11.1	9.9	10.1
Permanent Set		(2.4)	(2.4)			(1.1)	(1.2)	(1.7)	(1.0)	(1.9)	(1.7)	(1.9)	(1.9)	(.6)	(1.5)	(1.6)	(1.0)	(.9)	(1.0)	(2.4)	(2.4)	(8.5)		(1.0)	(.5)	(1.3)

.080" thick 50 in-lb moment

Plot Symbol	□	▲	△	○	▫	●
Specimen #	1	2	3	44	45	46
% Moment						
5						
10				1.0	1.0	
15		1.0		2.0	2.0	1.0
20	1.0		1.0		3.0	
25						2.0
30	2.0	2.0	2.0	3.0		
35					4.0	
40	3.0	3.0	3.0			
45				4.0		3.0
50		4.0			5.0	
55			4.0			
60	4.0			5.0		4.0
65		5.0			6.0	
70			5.0			
75	5.0			6.0		
80					7.0	5.0
85		6.0				
90	6.0		6.0	7.0		
95						6.0
100	6.5	6.8	6.5	7.4	8.2	6.3
Permanent Set	(1.5)	(1.7)	(1.7)	(1.1)	(1.4)	(.7)

Table 5. Raw Data for Bending Curves of .020 inch Specimens

.020" thick   10 in-lb moment

Plot Symbol	●	○	○	△	□	△	▲	□	●	○	○	△	▲	□
Specimen #	17		18			19			20			21		
% Moment														
5														
10	2.0	2.0	2.3	2.6	2.3	2.3	1.8	2.0	2.0	4.6	2.2	2.7	3.6	2.8
15														
20	3.6	3.5	4.4	4.9	4.4	4.3	3.3	3.4	4.1	8.3	4.3	4.8	6.2	5.1
25														
30	5.3	5.2	6.4	7.2	6.3	5.9	4.6	4.9	6.0	12.4	6.1	6.8	8.6	7.3
35														
40	6.6	6.7	8.3	9.1	8.4	7.6	5.8	6.4	8.0		7.6	8.9	11.2	9.4
45			9.5	10.6	9.6	8.4						11.3	12.7	11.6
50			11.0	12.3	11.2	9.4	7.2	8.1	10.3		9.9	11.3	14.6	12.0
55			12.6	14.3	13.0	10.3	7.5		11.9		11.0	12.8	17.0	13.5
60				17.2	15.4	11.6	8.8	10.0	13.8		12.3	14.7	20.6	15.6
65						13.0	9.6	11.2			14.1	17.1		
70						14.7								
75														
80														
85														
90														
95														
100														
Permanent Set														

Plot Symbol	●	○	○	△	□	▲	●	○	○	○	□	▲	●	○
Specimen #	22			23			24			25			26	
% Moment														
5														
10	2.3	2.3	2.1	1.8	1.9	1.9	2.0	1.6	1.7	3.4	2.9	2.8	2.7	2.5
15														
20	4.5	4.3	3.8	3.5	3.5	3.6	3.6	3.3	3.1	6.0	5.7	5.5	4.6	4.4
25														
30	6.7	6.1	5.5	4.9	4.9	4.9	5.0	4.6	4.5	8.1	8.5	8.3	6.7	6.3
35														
40	8.7	8.0	7.2	6.3	6.3	6.2	6.5	6.1	5.7	10.5	12.1	11.8	8.6	8.0
45	9.8	9.0	7.9								14.4	14.3		
50	11.1	10.1	9.1	8.1	7.6	7.7	8.9	7.3	7.0	14.3		18.4	10.8	10.2
55	12.6	11.3	10.0	8.9	8.5								12.6	11.3
60	14.4	13.0		9.9	9.4	9.2	9.7	9.1	8.4				13.8	13.0
65				11.0	10.1	10.1	10.9	10.0	9.1				16.0	15.0
70				12.1	11.6	11.1	12.0	11.0	10.8					
75				13.6	12.9	12.1	13.8	12.1	11.8					
80				15.2	14.6	13.3	15.2	13.3	12.4					
85				17.2		14.7		16.0	13.6					
90						16.5								
95						18.5								
100														
Permanent Set														

Plot Symbol	△	△	▲	■	●	○	□	●	○	○	△	▲	□
Specimen #	26	27			28			29			30		
% Moment													
5													
10	2.4	2.4	2.9	2.1	2.9	2.3	2.3	2.2	1.8	2.7	2.3	2.1	2.7
15													
20	4.3	4.1	5.1	4.4	5.0	4.5	4.1	4.1	3.6	4.7	4.3	3.4	4.7
25													
30	6.0	6.2	7.3	6.5	6.7	6.5	6.2	6.0	5.6	7.1	6.4	7.3	7.9
35													
40	7.8	8.1	9.3	8.6	8.1	8.6	8.2	7.9	7.4	9.5	8.8	9.7	9.4
45													
50	9.7	10.3	17.6	11.2	10.7	11.2	10.8	11.1	9.9	13.4	11.9	12.8	12.6
55	10.9										14.1	15.1	14.5
60	12.1	13.1	17.8	15.4	19.0	15.4	14.3	13.1	13.3		17.7	18.3	17.6
65	14.2	15.2		19.0	16.4	18.7	16.9	15.2	16.1				
70		18.0			20.3		21.2						
75													
80													
85													
90													
95													
100													
Permanent Set													

Table 6. Raw Data for Bending Curves of .010 inch Specimens

.010" thick 4 in-lb moment

Plot Symbol	○	□	▲	■	●	⌂	△	●	○	⌂	△	●	○	▲	△
Specimen #	31				32			33				34			
% Moment															
5					3.4	3.5	2.1	1.5	1.5						
10	3.3	3.7	3.3	4.3	6.8	6.3	4.0	2.8	2.7	2.2	3.0	2.7	2.7	3.3	2.6
15	5.1	5.6	4.9	6.2	10.2	9.1	6.1	3.8	3.6						
20	6.7	7.3	6.6	8.3	14.9	12.3	8.2	5.0	4.6	4.2	5.4	5.0	4.8	5.8	4.8
25	8.5	9.2	8.2	10.3		16.4	10.4	6.2	5.6						
30	10.4	11.0	9.9	12.8		22.4	13.3	7.3	6.4	6.0	7.4	7.1	6.7	8.0	6.9
35	12.7	13.3	11.7	15.9			16.8	8.4	7.4						
40	15.8	16.1	14.3	20.2				9.6	8.3	8.0	9.2	4.5	8.7	10.3	9.0
45	20.5		16.8					11.2	9.4						
50			22.4					13.0	10.3	10.4	11.1	12.5	10.8	13.4	11.7
55								15.2	11.8	12.1	12.2	14.4	12.3	15.5	15.3
60								18.4	13.3	14.4	13.8		14.1		15.7
65									15.3	17.2	15.6		16.5		
70									17.9	21.4	17.8		20.0		
75									21.0		20.9				
80															
85															
90															
95															
100															
Permanent Set															

Plot Symbol	△	▲	□	■	●	⌂	○	○	▲	⌂	●	/	∅
Specimen #	35				36			37		38		39	
% Moment													
5		2.2	2.6	2.0	2.7	2.3	2.2						
10	5.3	3.8	4.8	3.7	4.5	4.2	4.1	1.4	1.7	2.3	2.3	2.0	2.3
15		5.7	7.0	5.3	6.4	6.1	5.9						
20	10.4	7.6	9.2	7.0	8.4	8.0	8.0	3.0	3.2	4.1	4.0	3.7	4.1
25		9.4	11.9	8.9	10.8	10.0	10.0						
30	17.4	11.8	14.9	10.7	13.5	12.4	12.4	4.0	4.5	5.8	5.6	5.1	5.4
35	23.5	14.5	19.0	12.9	17.2	15.5	15.4						
40		18.3	25.6	15.9	22.5	19.7	19.5	5.0	5.6	7.2	7.3	6.4	6.9
45				20.0		24.2	20.5						
50				25.5				6.0	6.7	8.9	8.9	7.9	8.2
55													
60								7.0	7.9	10.7	10.8	9.5	9.6
65												10.4	10.6
70								8.0	7.0	12.0	12.3	11.4	11.2
75								8.7				12.7	12.3
80								9.3	10.5	16.1	16.8	14.1	13.6
85								10.0			19.0	16.1	14.9
90								10.8	12.1			18.6	16.6
95								11.6	13.1				18.6
100								12.4	14.1				21.4
Permanent Set								(2.1)	(4.6)				

Plot Symbol	⌂	□	■	●	▲	○	●	⌂	○	▲	□
Specimen #	40			41			42			43	
% Moment											
5											
10	1.6	1.8	2.0	2.7	2.0	2.0	2.8	2.6	3.1	1.7	1.6
15											
20	3.0	3.5	3.4	4.9	3.9	4.0	4.8	4.9	5.9	3.1	3.0
25											
30	4.4	5.0	4.8	6.7	5.3	6.0	6.8	7.1	8.1	4.6	4.2
35											
40	5.6	7.5	6.1	8.5	7.0	7.9	8.4	9.7	10.7	6.0	5.3
45											
50	7.1	8.0	7.5	10.6	8.5	10.1	10.3	12.5	13.6	7.5	6.2
55											
60	8.5	9.6	9.0	13.3	10.4	12.6	12.7	17.5	17.9	8.8	7.2
65	9.3	10.5	9.7	15.3	11.3	14.4	14.4		21.5	9.5	7.7
70	10.1	11.5	10.6	17.5	12.6	16.8	16.5			10.4	
75	11.0	12.6	11.4		14.1	19.8	19.7			11.1	8.7
80	12.1	14.0	12.5				24.3			12.0	9.2
85	13.3	15.5	13.6							13.1	9.7
90	14.8	17.5	15.1							14.3	10.4
95										15.3	11.0
100										17.0	11.5
Permanent Set										(4.1)	(1.1)

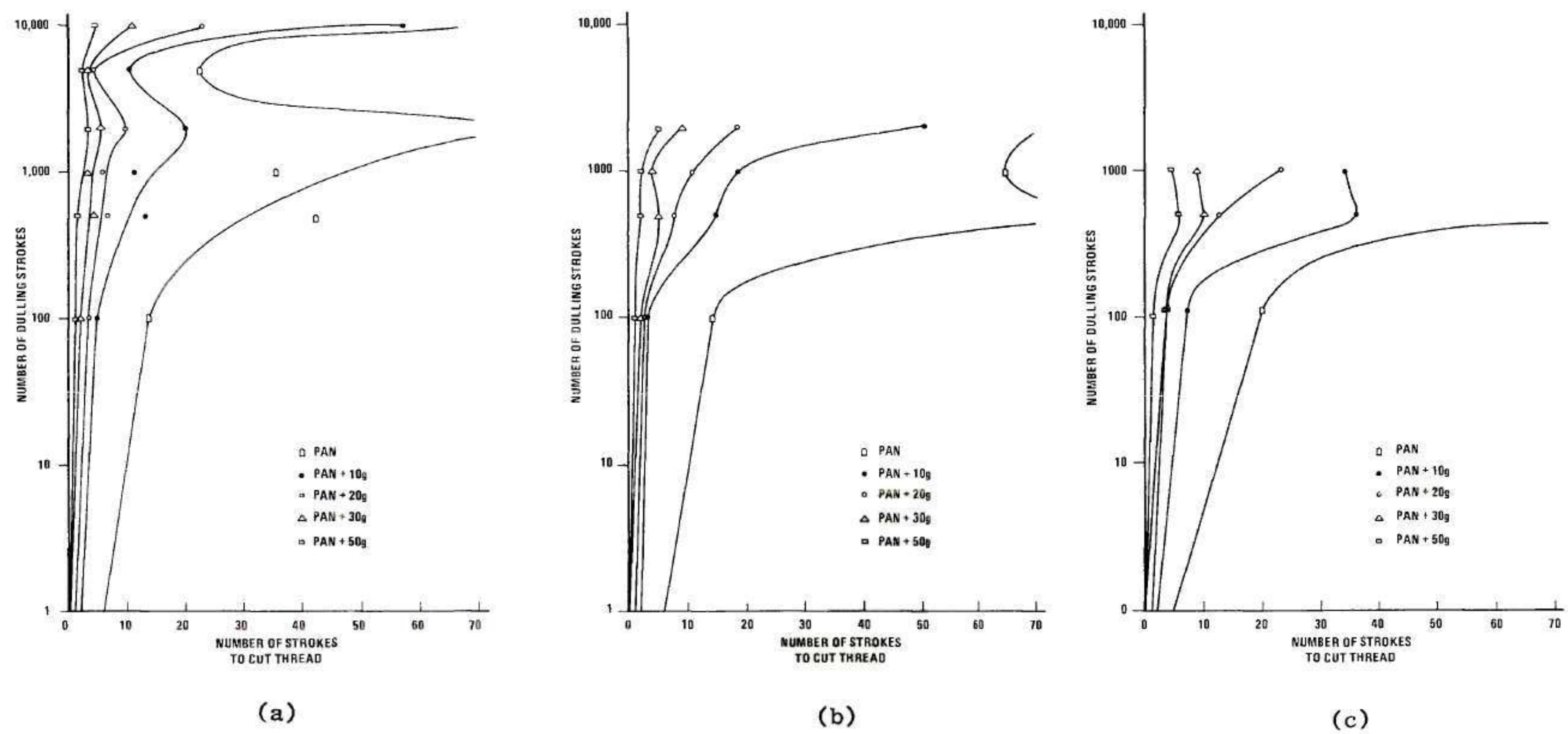


Figure 31. Dulling Curves for 26 Degree Edge Angle Knives: (a) Thin Edge, (b) Medium Edge, (c) Thick Edge.

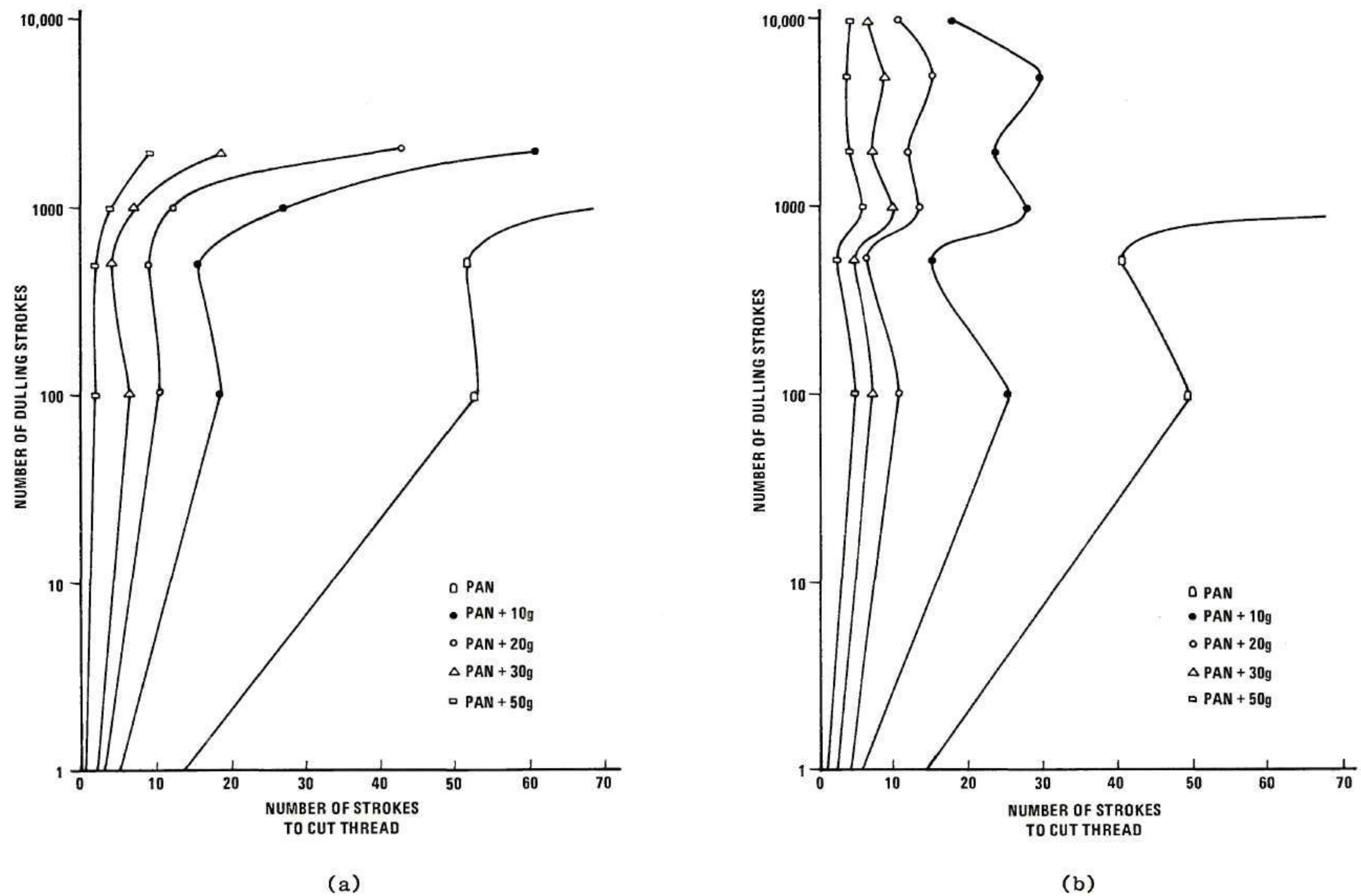


Figure 32. Dulling Curves for 47 Degree Edge Angle Knives: (a) Medium Edge, (b) Thick Edge.

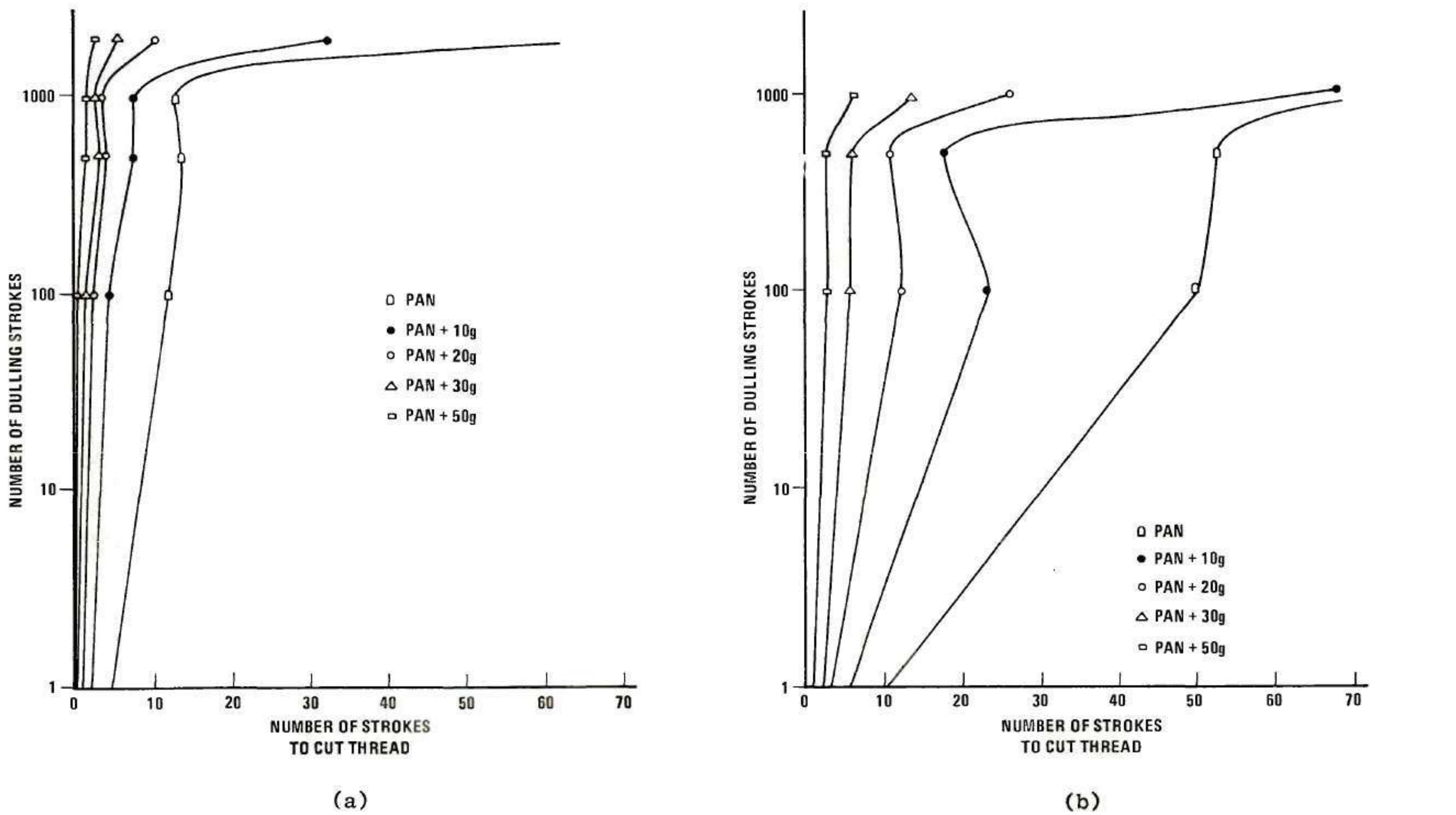


Figure 33. Dulling Curves for 54 Degree Edge Angle Knives: (a) Thin Edge, (b) Medium Edge.